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GEOLOGY OF THE BEATTIE GOLD MINE, DUPARQUET, QUEBEC.

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ABSTRACT.

This paper describes the geology of the Beattie mine, a gold deposit in northwestern Quebec. The mineralization is closely related in space, and possibly genetically, to an intrusion of syenite porphyry situated within an overturned syncline of Keewatin rocks along the eastern extension into Quebec of what is known as the Porcupine Belt.

No ore has been found very far from the syenite porphyry or related lath-porphyry dikes, and the orebodies are composite, consisting largely of bleached and brecciated Keewatin tuffs adjacent to altered syenite porphyry, both silicified and mineralized with very fine sulphides.

There are three major ore zones at the mine, two of the composite type mentioned above lying alongside pitching syenite lobes, and the third is an oreshoot within the syenite, following a fracture zone.

Extensive alteration of the syenite and Keewatin rocks was accompanied by the introduction of potash.

There are several ore types, but the most important is "breccia" ore, consisting of fragments of bleached and altered Keewatin rocks cemented by tiny quartz-carbonate stringers. Metallic mineralization is fine-grained pyrite and arsenopyrite. Adjacent to the "breccia" orebodies, and along fracture zones, are bodies of altered "gray massive" porphyry, also mineralized with pyrite and arsenopyrite.

The only important sulphides in the ore are gold-bearing pyrite and arsenopyrite, the former averaging 6½ per cent by weight, and the latter 1½ per cent. The gold content averages 0.14 ozs. per ton, and concentration followed by roasting and cyanidation is necessary to recover the values.

The structural aspects of the orebodies and their mineralogy suggest that this unusual deposit should be classed as mesothermal or even epithermal.

SINCE the inception of extensive underground development at the Beattie mine in 1933 no description of the geology and mineralogy of this important gold deposit has been published.[2] During the past several years the authors

[1] The structural mapping was largely carried out by Davidson, most of the microscopical and analytical interpretation by Banfield. The preparation of the paper has fallen to Davidson, as Banfield is at present an officer in the Royal Canadian Air Force. However, a copy of his doctor's thesis, submitted to Northwestern University, on The Geology of the Beattie Gold Mine, has been available and is the background for a large proportion of the material presented here.

[2] The total production of the Beattie mine to the end of 1942 has been 5,237,400 tons assaying 0.14 ozs. gold per ton. In addition a considerable tonnage of crude arsenic trioxide is marketed as a by-product.

have had an opportunity to study this deposit in considerable detail, and the results of these studies are the basis of this paper. Prior to this, in 1932–33, Dr. J. J. O'Neill,[3] under the auspices of the Quebec Bureau of Mines, mapped the surface outcrops in the vicinity of the mine and examined the few underground workings which had then been opened up during preliminary exploration. O'Neill's conclusion, based on the limited observations available, that "Bostonite porphyry sheared and silicified seems to be the favorable host rock for the ore" has been found by our later and much more extensive observations to be largely untenable. James, Buffam and Hopper have published reports on the geology in the vicinity of the Beattie gold mine.[4]

The Beattie mine, named in honor of its discoverer John Beattie, is located in northwestern Quebec, a short distance east of the Ontario boundary, and approximately 20 miles north and slightly west of Noranda. The property, staked in 1923, was finally brought into production in 1933 by Ventures, Limited, in association with Nipissing Mining Company. During the ten years prior to this, the prospect had been under option on several occasions, but it was not until 1930 that Beattie discovered the important orebody which has since been developed and forms the main source of production.

In the better known portion of the pre-Cambrian Shield of northern Ontario and Quebec two easterly trending, linear zones of ancient lavas and sediments, within the general granite area, are respectively known as the Kirkland Lake and Porcupine belts. The Beattie mine is situated on the extension of the latter belt approximately 95 miles east of the famous gold mining district of Porcupine.

A generalized geologic column for the pre-Cambrian rocks in this district is summarized below:

Keweenawan	—Diabase dikes
	—Fracturing and gold mineralization
Algoman	—Intrusions of syenite and quartz porphyries
	—Major folding
Timiskaming	—Conglomerates, arkose-greywacke
	—Unconformity
Keewatin	—Andesitic pillow lavas and associated sediments.

According to the geological surveys carried out by the Dominion and Provincial governments, the regional structure in the vicinity of the Beattie mine is an easterly pitching, overturned syncline with several thousand feet of Timiskaming sediments in the center surrounded by Keewatin volcanics. The Beattie mine lies on the north limb of the syncline, and the Keewatin series in this locality is, with few exceptions, overturned, dipping steeply north and facing south.

[3] O'Neill, J. J.: The Beattie gold mine, Duparquet Township. Quebec Bur. Mines. Ann. Rept., Part C: 3–28, 1932.

——: Beattie-Galatea map-area. Quebec Bur. Mines. Ann. Rept., Part C: 75–114, 1933.

[4] James, W. F.: Duparquet map-area, Quebec. Canada Geol. Surv., Summ. Rept., Part D: 75–96, 1922.

Buffam, B. S. W.: Destor area, Abitibi county, Quebec. Canada Geol. Surv., Summ. Rept., Part C: 82–104, 1925.

Hopper, C. H.: Mapped available workings and re-logged drill core. Company Report, 1934.

GEOLOGIC SETTING.

The Beattie ore deposits are closely related in space, and possibly genetically, to a syenite porphyry intrusive. On the surface the Beatttie syenite porphyry is a roughly tadpole-shaped mass with east-west trend, a length of approximately two and one-half miles, and a maximum width toward its western end of about 1,500 feet. It has been intruded into the Keewatin series along the north limb of the syncline near the contact with Timiskaming sediments. Some controversy still exists as to whether the syenite is of pre- or post-Timiskaming age. It has arisen from the occurrence of a peculiar "porphyry conglomerate" at or near the contact between the Timiskaming series and the Keewatin, containing boulders or porphyritic syenite strikingly similar in appearance to Beattie syenite. The "porphyry conglomerate" does not occur in the Beattie mine workings, and our surface study has not been sufficiently detailed to settle this problem.

The syenite intrusive at the mine consists mainly of medium-grained, pink to reddish porphyritic syenite. It is, however, a composite or compound intrusive, as towards the east it consists of several types differing somewhat in texture and composition. The most prominent of these types has been called *Bostonite* by O'Neill and appears to be a late differentiation phase of the syenite intrusive.

Microscopically the Beattie syenite porphyry consists of 80 per cent or more of feldspar. The phenocrysts vary both in size (averaging 2–10 mm.) and abundance. When their optical character can be determined the majority are found to be albite with lesser amounts of orthoclase and anorthoclase. Some phenocrysts, probably originally anorthoclase, show a breakdown to perthite with the albite parts quite clear and orthoclase much sericitized.

The only abundant mineral besides feldspar is hornblende, now largely altered to chlorite and carbonate.

Accessory minerals are sphene and apatite, both usually as small euhedral crystals.

The groundmass of the syenite porphyry consists of a felted aggregate of anhedral feldspar crystals. Their average size is from 0.2–0.5 mm., and tests by refractive index liquids show the feldspar to be anorthoclase.

Some degree of alteration is always present in the syenite. The most abundant alteration product is sericite formed at the expense of the feldspars. Kaolin is also widespread, but less abundant than sericite. Chlorite and carbonate are alteration products after hornblende, and carbonate is also associated with sericite as an alteration of the feldspars.

The reddish color of the syenite is due to hematite dust. Much of the hematite, and hence the red color, appears to have resulted from the breakdown of the hornblende and oxidation of its ferrous iron. Hematite dust is abundant in the feldspar commonly associated with sericite and carbonate.

Associated with the main syenite mass at Beattie, and in all probability derived from the same magma source, are numerous dike-like bodies of distinctive lath-feldspar porphyry. They are found cutting the syenite and also in the surrounding Keewatin rocks. The smaller dikes are irregular, but

some of the larger ones which average ten to twenty feet in width are persistent both along strike and down dip. They are usually of reddish cast and composed of abundant lath-shaped feldspars in a fine-grained trachytic groundmass. The phenocrysts are oriented parallel to the dike walls, entirely so in the narrow dikes, and marginally for several feet in the larger ones.

Microscopic examination of thin sections shows that the lath-porphyry dikes are composed of 85–95 per cent feldspar, and both the tabular phenocrysts and groundmass feldspars are orthoclase. Ferro-magnesian minerals are almost entirely absent, and with the exception of a little chlorite, the remaining minerals (apatite, sphene, ilmenite) are accessories and alteration products.

The Keewatin rocks surrounding the syenite porphyry, where exposed in the workings of the mine, consist mainly of pillow lavas and pyroclastic sediments. The lavas are predominantly thin flows, dark green, with prominent ellipsoidal or pillow structures. As mentioned previously, they represent the north limb of an over-turned syncline and, except locally, dip steeply north while facing south. They are generally slightly schistose and like most of these ancient rocks exhibit the typical chloritic and carbonate alteration.

Although the mineralogical texture of these rocks has been largely obliterated, the larger structures, such as pillows and breccia tops, have been preserved with remarkable fidelity. In many places the elongated character of the pillow structure suggests that they have been drawn out by the stresses resulting from folding. Microscopically the pillow lavas now consist almost entirely of secondary minerals: 40 per cent chlorite, 20 per cent calcite, 15–35 per cent fine-grained intergrown feldspar crystals, some of which may be primary, and a small amount of secondary quartz, sericite and opaque minerals.

The pyroclastic sediments are of several types, the most prominent being a finely banded green andesitic tuff. This important member lies along the north contact of the porphyry, and apparently increases in width towards the west. Intercalated within this horizon are a few thin flows of pillow lava. Other members of the Keewatin series are gray, fine-grained, thinly bedded sandy sediments with which are associated narrow bands of black slaty material and some bluish cherty bands.

Another rock type forms an important member of the Keewatin series. It is a peculiar greenish schist which, for lack of a better name, has been called "speckled schist." Texturally it varies from place to place, but the development of dark green micaceous flakes, giving rise to the speckled appearance, is usually diagnostic. Most likely it is a metamorphosed tuffaceous sediment. One horizon of "speckled schist" lies south of the andesitic tuff, and in the northwestern section of the mine forms the only horizon marker which can be recognized with any degree of certainty. A variant of this rock develops a pepper and salt texture with conspicuous white specks.

The total thickness of the Keewatin series exposed in the workings of the mine is approximately 2,000 feet.

With the possible exception of one locality, the Timiskaming rocks are not exposed in the mine workings and hence are unimportant from the economic viewpoint. Several drill holes, however, have penetrated this series south

of the syenite porphyry. They consist of schisted and metamorphosed sediments as well as conglomerate with typical red jasper pebbles.

Structure.

The general shape of the syenite-porphyry mass at Beattie is fairly well known. The western end of it pitches sharply east, and it divides below the second (or 350-foot) level into a north and a south lobe. The inverted trough between these lobes is asymmetrical in shape (Fig. 1). The south contact of

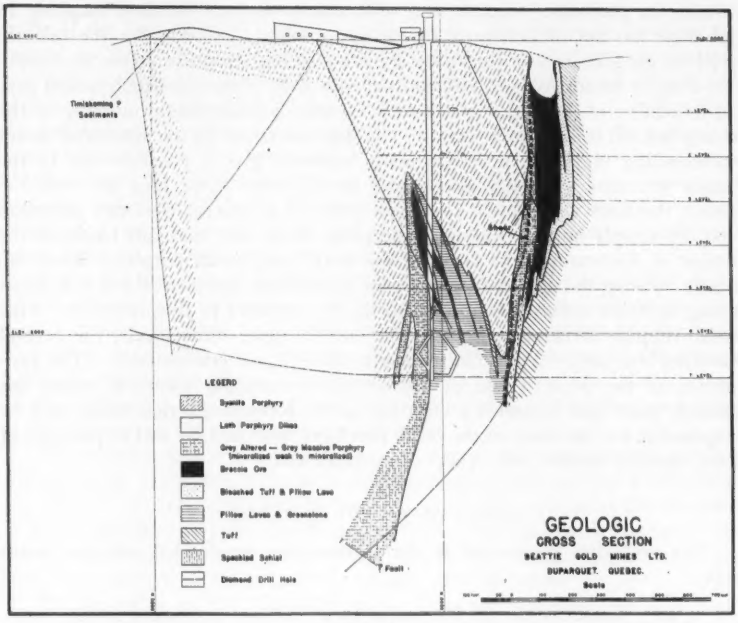

FIG. 1.

the north lobe dips north at about a 60-degree average, while its north contact, disallowing minor pendulous apophyses, is slightly convex in shape. This structure, plus the easterly pitch, gives rise to a diminution in the size of the north lobe until the sixth or 1,000-foot level is reached. Here the south contact becomes steeper with corresponding steepening of the easterly pitch. Development work on the new levels below the sixth has not at the time of writing advanced far enough to establish the structural picture at these new lower horizons.

The south porphyry lobe also pitches east, but as it is more symmetrical it maintains its size and shape with more regularity. Its western extremity has been outlined in a general way by diamond-drilling.

Recently a long exploration drift, with accompanying lateral diamond-drilling, has explored the south contact of the main porphyry mass on the third level in the central and eastern sections of the property. A large inclusion of altered "greenstone" with an indicated easterly pitch has been outlined within the syenite at this horizon. The rocks traversed on the south side of the syenite are for the most part intensely altered pillow lavas.

By drilling to the south, schisted and metamorphosed sediments, presumably Timiskaming, have been located.

As pointed out above, the Beattie syenite, as far as known, lies entirely within the Keewatin volcanic and sedimentary rocks. Detailed mapping in the mine has not satisfactorily solved the problem as to whether the easterly pitch of the syenite was controlled by pre-existing structure in the Keewatin. No drag or minor folds of any consequence were observed which would give an indication of the major structure. Locally, considerable crumpling of the thinly bedded tuffs is to be seen. The dip and strike of the Keewatin series surrounding the north porphyry lobe, however, give a possible clue to the major structure. On the second and third levels, where they are well exposed, the tuffs west of the porphyry strike in a general west-east direction and dip steeply north. Similarly the pillow lavas and thin tuff bands in the wedge of Keewatin rocks between the north and south porphyry lobes dip north. Along the northern flank of the north lobe, however, there is a slight swing in strike toward the north, and the dip reverses to steeply south. This south dipping structure extends east, on the upper mine levels, for several hundred feet before a reversal to north dip is again encountered. The projection of the western end of this structure naturally shows a rather flat easterly pitch and indicates a buckling in the Keewatin series which may be responsible for the shape of the north porphyry lobe, and, as will be pointed out later, possibly controls the North orebody as well.

STRUCTURE OF THE OREBODIES.

The orebodies discovered at the Beattie may be divided into two main types:

(a) Those within the Keewatin rocks in close proximity to the porphyry
(b) Orebodies in the prophyry usually associated with recognizable fracture zones.

Of these two types, the first is by far the more important, accounting for approximately 75 per cent of the tonnage mined.

The North Orebody.

The North or main orebody, consisting principally of altered, brecciated and mineralized tuff, is situated along the north side of the Beattie porphyry close to its western end. It pitches east in closely parallel relationship with the porphyry. On the third level the ore is 1,700 feet long and has a maximum width of 100 feet. At its south contact is a varying width of "gray

massive," highly altered and mineralized porphyry. The values in this are usually high enough to permit mining most of it along with the main orebody. Within the altered porphyry is a persistent mineralized sericite schist zone of varying width striking more or less parallel to the north contact of the porphyry. This mineralized shear extends to the east, usually within, but close to, the north contact of the porphyry. To the east on the upper mine levels, it is actually along the north contact. To the west, it leaves the porphyry and has been traced as a narrow band of mineralized schist for a short distance out into the Keewatin rocks.

The North orebody in the Keewatin rocks has formed largely at the expense of the finely banded andesitic tuff horizon. On the upper levels in the central section of the mine where mineralization was most intense this tuff has been so changed by alteration and mineralization as to be almost unrecognizable. To the west, as the extremity of the porphyry is approached, the tuff horizon becomes separated from the porphyry contact by a band of "speckled schist." This latter rock, comparatively speaking, is an unfavorable host, and the ore feathers out in the tuff to the north of it. One small orebody, called the "C," has been found at a considerable distance from the porphyry extending down in the tuff horizon between the second and third levels from the western end of the main orebody.

In the western end of the open pit, by which method the upper part of the North orebody is mined, and in the western workings on the first and second levels, an altered pillow lava could at one time be seen within the ore zone. The pillow lava is intensely altered (Fig. 2), but the outlines of the pillows are well preserved in places. The rock itself is a comparatively poor ore host as this material forms a low-grade block intercalated within the ore formed at the expense of the tuffs on either side of it.

The western end of the North orebody pitches east at about 30 degrees, following the north porphyry lobe, and its eastern limit on the levels above the fifth has an irregular pitch to the west. On the sixth level the ore zone is approximately the same size as on the fifth. On the new levels below the sixth, development work has not yet proceeded far enough to give a definite structural picture of the situation at those new horizons.

The buckling in the Keewatin rocks has been suggested as a possible controlling influence on the easterly pitch of both the north porhpyry lobe and the main orebody. This buckling undoubtedly tended to increase permeability in the tuffaceous horizon along the north side of the porphyry. In any event, the relationship between the easterly pitch of the porphyry to the North orebody is clearly demonstrated by a study of the longitudinal section (Fig. 3, q.v.).

The small "C" orebody, extending as a pendulous protuberance below the upper western end of the main body, is of interest in this connection as it demonstrates that structural complexities in the tuff horizon had a definite influence on ore deposition. The "C" orebody bottoms at the third level and is located where the andesitic tuff horizon reverses for a short distance from north to south dip. This small buckle in the andesitic tuff is analogous to the larger one along the northwestern flank of the north lobe.

To the east, beyond the limit of the North orebody, the flank of the porphyry is more or less parallel in dip and strike to the Keewatin. There is locally considerable alteration and a little mineralization but not much ore at the contact here. The lack of ore shoots along this section of the contact is probably due in part to the unfavorable character of the wall rock, the permeable tuffs having locally given way to altered pillow lavas at the contact.

FIG. 2. Bleached and altered pillow lava. App. 0.05 natural size.

The "A" Orebody.

The "A" orebody was accidentally discovered during the course of sinking the main shaft. It lies along the north contact of the south porphyry lobe in the reentrant between the north and south porphyry lobes. The asymmetrical wedge of Keewatin rocks between the porphyry lobes consists primarily of a series of thin pillow lavas. Intercalated within the pillow lavas is a relatively narrow band of thinly bedded tuffs.

The "A" zone has been extensively developed and mined from its apex above the third level to below the fifth. In the Keewatin rocks below the fourth level the ore divides into two strands, one of which is definitely localized along the favorable tuff horizon, and geological projection suggests that the other is along a flow top. In the adjacent porphyry, along the north contact of the south lobe, is a wide zone of low-grade mineralization.

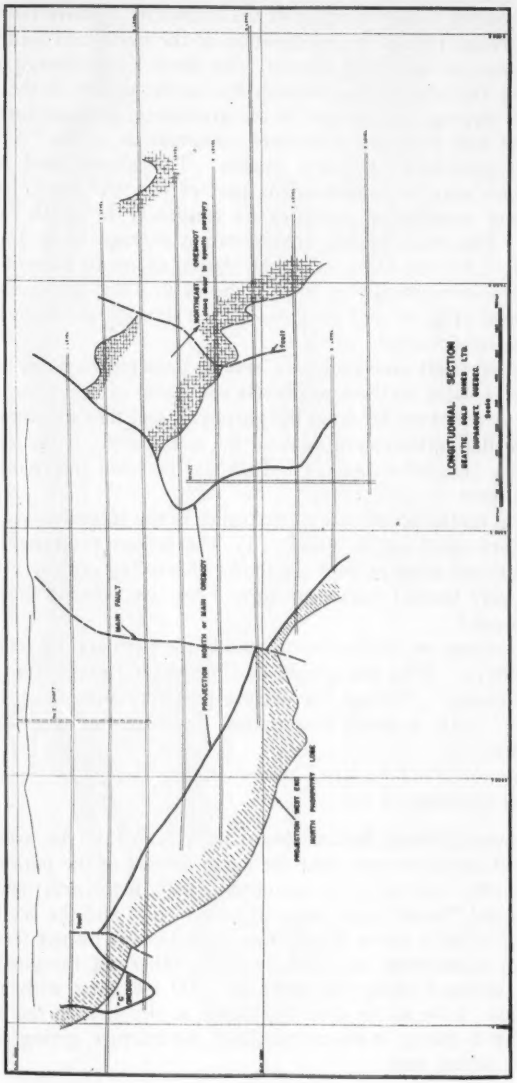
LONGITUDINAL SECTION
BEATTIE GOLD MINES LTD.
DUPARQUET, QUEBEC.
MAIN FAULT
PROJECTION NORTH OF MAIN OREBODY
NORTHEAST OREBODY

FIG. 3.

The oreshoots dip north and pitch east, controlled by the attitude of the porphyry in relation to the structure of the Keewatin. Above the third level, the inverted trough formed by the junction of the north and south porphyry lobes pitches east at about 30 degrees. As these lobes diverge with depth and pitch east, the intersection between the north contact of the south lobe and the north dipping tuff horizon in the greenstone becomes foreshortened, and below the fifth level the downward continuation of the "A" ore zone, although still persistent, is much smaller. The altered and mineralized porphyry, which may be considered as part of the "A" zone, pitches east, and preliminary exploration indicates its continuity in depth on the new lower levels. The width of this mineralization averages over 150 feet, and although most of it is too low-grade to be classed as ore by present standards, it may be possible eventually to mine some of it. The accompanying plan of the third level (Fig. 4) and the cross-section through the main shaft (Fig. 1) show these relationships.

A number of small orebodies in a similar geological setting to the "A" zone have been located on the lower levels southwest of it. These small orebodies do not extend very far from the porphyry, and they all appear to pitch east, following the northwestern flank of the south lobe. They are localized along permeable (banded sediments and schists) horizons where the porphyry has truncated them.

In summing up the occurrence of orebodies in the Keewatin rocks, certain empirical factors stand out in relief: (a) The largest orebodies at present known are localized along or near the flanks of pitching porphyry lobes; (b) horizons of finely banded tuffs near these lobes are favorite places for the localization of ore.[5]

Up to the present, no ore has been found in the surrounding rocks very far from the porphyry. Why this should be is a question that has not been answered satisfactorily. Perhaps the syenite porphyry may have represented a "hot center" with a steep temperature gradient into the surrounding Keewatin series.

The Northeast Orebody.

The Northeast orebody occurs almost entirely within the syenite, along the sheared and fractured zone near the north contact of the porphyry. The shear zone, briefly referred to in connection with the North orebody, is a fairly well defined "break" with steep to vertical dip, and the width of mineralized syenite along it varies from a foot or so to over twenty feet. It contains shoots of commercial ore, and there are others of marginal material.

The main oreshoot along the shear is 1,200 feet long with an average width of 15 feet. Like all the other orebodies, it pitches east, but the control here is related to a change in dip and strike of the fracture, giving rise to lines of intersection raking east.

[5] Since this paper was written new ore has been encountered south of the main Beattie porphyry mass on the sixth level. It occurs along silicified fracture zones in bleached pillow lavas, forming narrow but comparatively rich oreshoots.

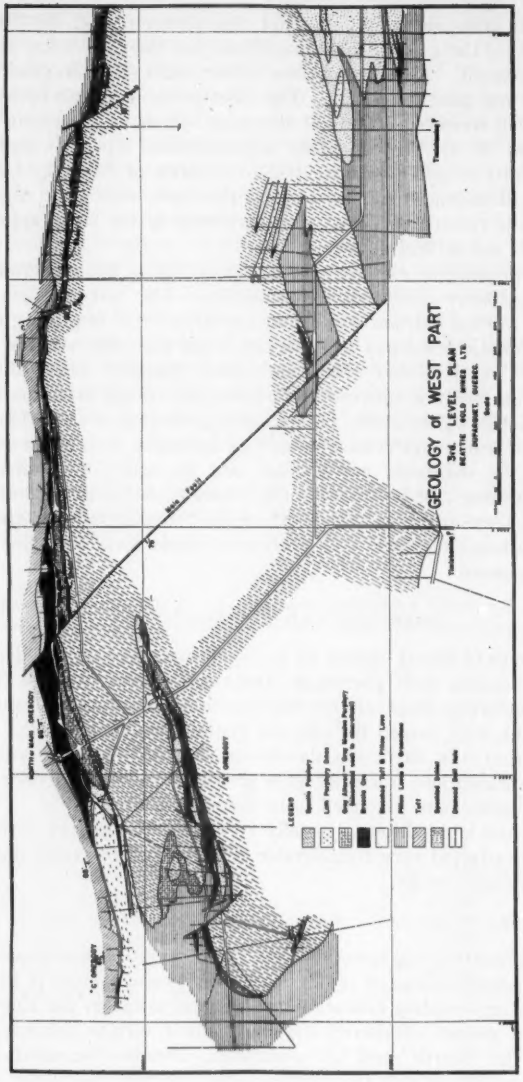
GEOLOGY of WEST PART
3rd. LEVEL PLAN
BEATTIE GOLD MINES LTD.
DUPARQUET, QUEBEC.
LEGEND

FIG. 4.

Post-Ore Faulting.

Numerous post-ore faults interrupt the continuity of the Beattie orebodies. Most of these are of small magnitude, but there are a few with considerable displacement. Two sets of these minor faults strike in general N 30 E and N 30 W and have steep dips. The most prominent fault is that between the eastern and western sections of the mine. It is of composite character, striking about N 45 W with steep southwesterly dip (75 degrees), and subsidiary faults related to it give rise to a series of irregular fault blocks. The amount of displacement has been worked out with some degree of accuracy, and the eastern segment moved, relative to the west, approximately 100 feet south and 40 feet down.

A rather prominent east-west fault follows along the mineralized shear zone in the porphyry close to its north border. The movement on this fault has not been worked out, but it does not appear to be of large magnitude.

A characteristic feature of the post-ore faults and breaks is the formation along them of veins of very coarse carbonate, generally white calcite. The carbonate veins are not universally present, but range from paper-thin to well over a foot in width, locally cementing fragments of ore as a fault breccia. Typical gouge seams and crushed zones, occasionally with graphite development where the sediments are crossed, are frequently encountered. The amount of crushing and gouge naturally depends on the type of rock cut by the fault. In some instances a fairly strong fault may appear as a more or less inconspicuous break in brittle rocks, while in friable rocks the same fault will be very pronounced.

ALTERATION AND MINERALIZATION.

The sequence of events leading up to the formation of the ore deposits was probably continuous, with alteration preparing the way for ore deposition. Whether the solutions which altered the syenite porphyry and the surrounding Keewatin rocks, and formed the ore, are genetically related to the syenite is an open question. In any event the syenite was in place and solid enough to be locally sheared and fractured, thus providing channelways for solutions which may possibly have ascended from the same source.

Under favorable conditions (usually recognizable zones of permeability) these solutions effected very considerable changes in the syenite itself and in the nearby Keewatin rocks.

Alteration of the Syenite.

Although alteration and mineralization in the syenite is less important than that in the Keewatin rocks, it is discussed first as the syenite is the nucleus for the halo of surrounding alteration and mineralization in the Keewatin.

The largest masses of altered and mineralized syenite porphyry are associated with the "North" and "A" ore zones. Similar, but smaller, masses are found in association with the northeast shear, giving rise to the Northeast oreshoots.

The best opportunities for study of the alteration and mineralization of the

syenite porphyry have been found in the main shaft crosscuts. These crosscuts expose excellent cross-sections of the north porphyry lobe and the north contact of the south porphyry near the "A" orebody.

As the north contact of the north lobe is approached the red color of the syenite disappears by gradation to "gray altered" porphyry and thence to "gray massive" (altered porphyry) as the degree of alteration increases. The latter rock, as its name implies, is of massive appearance and gray in color. Most of it, as previously mentioned, carries values sufficiently high to permit mining along with the adjacent North orebody in the Keewatin. All gradations exist between the red syenite porphyry and "gray massive," and locally there are unaltered inclusions of the former in the latter.

The "gray massive" along the south side of the North orebody is closely associated with the east-west shear zone near the north contact. The Northeast ore shoots, which are related to the same fracture, consist in part of similar altered and mineralized porphyry, and in most places there is a gradual merging into typical red syenite with increased distance from the shear.

That the alteration of the syenite is definitely connected with the ore is borne out by the fact that the "gray massive" always contains gold and sulphides; the amount of gold and sulphides is in general proportional to the degree of alteration.

A number of analyses were made to study the chemical changes resulting from the alteration of the syenite to "gray massive." These analyses are set forth in Table 1.

TABLE 1.

CHEMICAL COMPOSITION OF ALTERED AND UNALTERED SYENITE PORPHYRY

	A.	B.	C.
SiO_2	56.17	55.94	53.28
Al_2O_3	18.19	17.15	15.88
Fe_2O_3	1.868	0.923	0.308
FeO	2.02	2.52	2.66
Fe	0.113	0.434	1.154
MgO	1.37	1.45	2.46
CaO	0.28	0.25	0.22
Na_2O	5.39	4.56	2.18
K_2O	4.16	4.31	9.02
H_2O	0.14	0.08	0.18
TiO_2	0.368	0.137	0.211
MnO	—	—	—
$CaCO_3$	11.70	13.10	11.50
S	0.124	0.495	1.31
As	0.013	0.006	0.023
Cu	0.008	0.01	0.009
Au oz./T	Trace	Trace	0.12
Total	101.914	101.365	100.395

Location: Main shaft crosscut, First Level.

A—Syenite porphyry, red, somewhat altered.

B—Gray, altered syenite porphyry.

C—"Gray Massive." Altered syenite porphyry.

Analyses: F. R. Archibald and P. Jacques, Research Department, Beattie Gold Mines (Quebec) Ltd. Alkali analyses by Ledoux & Co., New York.

In comparing the chemical analyses, it will be noted that the most striking change is the marked increase of potash and loss in soda in the analysis of the "gray massive." The decrease in the amount of ferric oxide was expected as it could be foretold by the color change from red to gray. The mineralization is shown by the gold content of the "gray massive" and the increases in sulphur and arsenic.

The microscopical comparison of rocks similar to those analyzed reveals some interesting features. With the appearance of mineralization the feldspars undergo a pronounced change, and in the gray altered syenite porphyry the anorthoclase has completely broken down into albite and orthoclase; in such cases the groundmass consists of anhedral crystals of albite and orthoclase with an increasing number of lath-shaped grains.

In the "gray massive," the majority of the feldspar crystals are lath-shaped, and judging from the high potash-soda ratio, they are orthoclase. The change in crystal shape is perhaps due to the replacement of soda feldspars by potash-rich solutions, yielding lath-shaped orthoclase individuals. Deformation of the orthoclase crystals at the time of formation, or shortly thereafter, is suggested by a combination of features. These are the brecciated appearance of some of the feldspar phenocrysts, partially detached cleavage fragments, and the arrangement of lath-shaped crystals of the groundmass in parallel around phenocrysts. Fracturing of a recurrent nature probably persisted throughout the general period of mineralization, and there appear to have been several stages in the formation of "gray massive"; fractures in secondary lath crystals, for example, are in places filled with quartz and carbonate.

Other minerals present in the altered prophyry are apatite, titanite or sphene, ilmenite and leucoxene. Apatite is resistant to alteration and is a relict mineral of fresh appearance even in intensely altered porphyry.

Alteration of the Keewatin.

The regional metamorphism of the Keewatin is characteristic of the belts of these rocks in northern Ontario and Quebec. As described previously, the "greenstones" consist almost entirely of secondary minerals, principally chlorite and carbonate.

Near the orebodies associated with the Beattie syenite, the dark green chloritic lava flows and associated tuffaceous sediments have been bleached to a pale greenish yellow color. Photographs illustrating the bleaching of various members of the Keewatin rocks accompany this paper. Of perhaps unusual interest is the bleached pillow lava. The outlines of the pillows are preserved with remarkable fidelity as darker borders surrounding light yellow to buff colored interiors. This is well illustrated in Figure 2 and is perhaps due to an original aphanitic texture of the pillow borders.

The alteration surrounding the orebodies varies within fairly wide limits. South of the porphyry on the third level the pillow lavas have been bleached and altered over a wide area. Systematic diamond-drilling has intersected numerous ore patches, but few structures, such as favorable tuff horizons, along which the values could concentrate, have so far been found.

Along the borders and ends of the North and "A" orebodies, bleaching of the surrounding Keewatin rocks is generally conspicuous, extending for varying distances, usually greater in the case of tuffaceous beds than in pillow lavas.

Chemical analyses comparing the bleached and unbleached andesite are tabulated in Table 2.

TABLE 2.

CHEMICAL ANALYSES OF BLEACHED AND UNBLEACHED ANDESITE.

(See Fig. 5.)

	Andesite (Dark "Greenstone").	Bleached Andesite.	Increase.	Decrease.
SiO_2	29.70	63.13	33.43	—
Al_2O_3	6.45	12.10	5.65	—
FeO, Fe_2O_3	24.77	3.89	—	20.88
MgO	3.26	0.90	—	2.36
CaO	0.58	0.36	—	0.22
Na_2O	0.53	2.62	2.09	—
K_2O	0.57	3.14	2.57	—
TiO_2	0.79	1.04	—	0.25
MnO	1.63	0.25	—	1.38
$CaCO_3$	18.75	9.12	—	9.62
Volatiles (calculated)	11.24	2.88	—	8.36
Total	98.27	99.44	43.74	43.07

Location: 54 Drift, Beattie mine, south wall, near main crosscut. (Samples 10 feet apart.)
Analyses: F. R. Archibald and P. Jacques, Research Department, Beattie Gold Mines (Quebec) Ltd. Alkalies by Ledoux & Co., New York.

These analyses show that the bleaching was attended by marked increases in SiO_2, Al_2O_3, Na_2O and K_2O, indicating a feldspathization with the formation of orthoclase and albite or, assuming they are present as one mineral, anorthoclase. The color change from dark green to light yellow results from the breakdown of the chlorite with consequent removal of iron oxides and magnesia. Incidentally, some of the iron may have been redeposited locally, as the unbleached andesite shows an unusually high content of iron oxides.

Mineralization.

The sequence of stages resulting in the formation of the arsenical gold ore at Beattie is complex. It is thought that the earliest solutions of the ore-forming period altered the porphyry and bleached adjacent members of the Keewatin series. This was followed by a period of mild inter-mineralization fracturing and brecciation, permitting the somewhat later ore-carrying solutions to concentrate their values in this altered and presumably favorable host rock. The brecciation of the bleached and altered rocks was a guide for subsequent mineralization because where the bleached rock in the zone is not shattered there is comparatively little sulphide mineralization. An illustration of breccia ore, or as it is sometimes called at the mine, "blue breccia," is shown in Figure 6. Breccia ore has formed exclusively within the Kee-

watin rocks, and as mentioned above, a very large proportion of it, particularly in the main orebody, has been localized at the expense of a favorable tuff horizon.

In the breccia ore, and confined to it, are numerous small lenticular feldspathic "dikes," rarely exceeding two feet in width. These so-called dikes are fine-grained, ranging in color from gray to reddish, and microscopically they consist largely of feldspar, principally orthoclase, but where altered, carbonate, chlorite and quartz are present in varying amounts. The occurrence of these peculiar orthoclase dikes in the breccia ore suggests that they are connected with the early stages of mineralization and probably formed from the same

FIG. 5. Partially bleached andesite ("greenstone"). App. 0.05 natural size.

solutions which brought in the large amounts of potash added during the alteration of the syenite porphyry and Keewatin rocks. Thin sections of these unusual dikes, and refractive indices tests in immersion liquids suggest that the potash feldspar they contain may be adularia as the better developed crystals in places have a rhombic outline suggestive of the adularia habit. The dikes, like the bleached tuffs and pillow lavas, have been brecciated and later silicification accompanying the introduction of the ore minerals has produced a peculiar pseudo-oölitic texture to be described below.

In the Beattie mine there are several more or less distinct textural types of ore. In general these are related to the various rocks forming their walls,

and the major subdivisions of ore in the porphyry and in the Keewatin rocks have already been referred to.

The orebodies in the Keewatin series provide approximately 75 per cent of the tonnage mined and consequently will be classified first.

Breccia Ore. This type of ore has accounted for over half the Beattie production. It consists of a grayish blue to buff colored breccia of angular to sub-angular fragments cemented by a network of tiny quartz stringers. The fragments consist of bleached and altered tuffs (locally pillow lavas), and fine-grained pyrite is the only metallic mineral generally visible to the naked eye.

FIG. 6. High-grade breccia ore. Silicification darkens center of photographed area. App. 0.08 natural size.

A variant of breccia ore is buff breccia of light yellowish color. This material is not as well brecciated or mineralized as the typical ore and is often marginal to it or forms horses of low-grade within the main orebody.

The occurrence of lenticular orthoclase dikes within the breccia zones has been referred to, and where brecciated and mineralized they form an important part of the breccia ore.

The alteration and mineralization of the orthoclase dikes, which constitute almost 15 per cent of the breccia ore, is of such an unusual type that it warrants a more detailed description. The dikes, as mentioned above, are confined to the breccia ore zones and occur most abundantly associated with the

North orebody. Where not brecciated and mineralized they are usually light pink in color and have a fine-grained compact appearance.

Brecciation followed by silicification produced changes resulting in a peculiar pseudo-oölitic texture. This texture is often visible megascopically, and the term "dike breccia" has been coined to describe it. The accompanying microphotograph (Fig. 7) illustrates this peculiar texture.

Studies of a series of thin sections indicate that after brecciation siliceous solutions penetrated along the fractures and attacked the orthoclase. The solutions apparently removed the potash leaving the alumina behind as a dusty residue of kaolin-like appearance. When the residue reached a width of about 0.03 mm., further replacement was prevented, and as this reaction was taking place along a network of fractures the unaltered orthoclase pro-

FIG. 7. Microphotograph of "dike breccia" with oölites. × 33.

tected by the dutsy rim appears as rounded or elliptical areas suggesting oölites.

The inter-oölite areas consist of fine-grained quartz together with small amounts of chlorite, sericite, leucoxene, and calcite. Locally, where silicification was more intense, the solutions broke through the protecting rim and partially replaced the orthoclase forming the nuclei of the "oölites."

Carbonate deposition accompanied and followed the last stages of silicification, and in places where it has replaced quartz and feldspar, the original outline of the oölite is preserved by the kaolin-like residue.

The silicified and carbonated "dike breccia" is mineralized with fine pyrite and arsenopyrite and forms some of the richest ore in the mine, averaging between a quarter and a half ounce gold per ton.

Mineralized Tuffs. The "C" orebody consists primarily of finely banded mineralized tuffs. In this type of ore, bleaching and brecciation are not con-

spicuous, but rich sulphide stringers selectively replace certain bands in the tuff. A good illustration of this ore type is shown in Figure 8.

Other small orebodies, occurring southwest of the "A" zone and somewhat analogous to the mineralized tuffs, are mineralized schists in the Keewatin series and also mineralized silicified lenses within the gray sediments. This latter type is of dark cherty appearance with irregular sulphide mineralization.

The ore types formed within the porphyry may be classified under three main subdivisions:

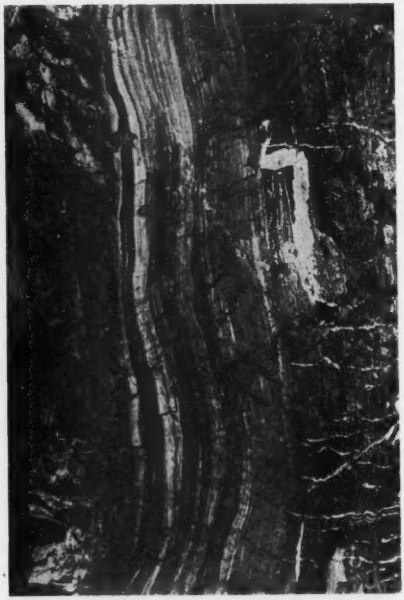

FIG. 8. Selective bleaching and mineralization in banded tuffs. App. 0.04 natural size.

"Gray Massive." The altered mineralized porphyry called "gray massive" has accounted for a fairly large portion of the ore developed at Beattie. Its origin and formation have been discussed above in connection with the alteration of the syenite. The gray altered porphyry is usually marginal to "gray massive" and although mineralization in this is sparse, there are large tonnages of this low-grade material, some of which perhaps can be mined under favorable conditions.

Mineralized Shear Zones. The northeast shear zone, and other less well defined breaks in the porphyry, have in places been silicified and mineralized to such an extent that they constitute small but important orebodies. These oreshoots are really composite in type, consisting along the shear or frac-

ture partly of irregular, gray-blue cherty quartz veins and associated carbonate mineralized with fine pyrite surrounded by varying widths of "gray massive." An illustration of the mineralization along the northeast shear is shown in Figure 9.

Lath Porphyry Dikes. Some of the lath porphyry dikes are altered and mineralized and carry sufficient gold values to permit extraction. Numerous small dikes of this type occur within the main orebody and are mined along with it. A few of the larger dikes constitute small independent orebodies, notably near the western limit of the south porphyry lobe, and within the altered pillow lavas in the south contact area.

FIG. 9. Mineralized shear zone in altered syenite porphyry. App. 0.1 natural size.

Tension Veins. Toward the close of the ore-forming period numerous tension fissures developed, principally within the altered syenite. They are of two ages and often form a regular pattern. Filling is coarse quartz and carbonate, with subordinate chlorite, chalcopyrite, sphalerite and galena. A little fluorite has been noted in veins of this type. They rarely carry any values, but one of them or a vein of similar type contained considerable free gold where it intersected the main orebody.

MINEROLOGY OT THE ORES.

The important metallic minerals in the Beattie ores are gold-bearing pyrite and arsenopyrite. The sulphide content is approximately 8 per cent

by weight, averaging 6½ per cent pyrite and 1½ per cent arsenopyrite. Other metallic minerals are present in very minor amounts. They are chalcopyrite, sphalerite, galena, molybdenite, and in a few places a little visible gold. Small amounts of ilmenite and magnetite are present, but these are thought to represent residual minerals derived from the altered rocks within the ore zone.

A wide band of marcasite mineralization along a fault zone in the Keewatin rocks north of the Beattie ore zones was discovered in the course of crosscutting for a diamond-drill station. It is an interesting occurrence, but as it contains no gold or other valuable associates has not been followed up.

The presence of essentially only two simple sulphides, namely fine-grained pyrite and arsenopyrite, in the Beattie ores is believed to be more or less unique among important gold producers.

The gangue of the various ore types at Beattie is generally composite, consisting of varying proportions of intensely altered rock fragments and introduced quartz and carbonate. The sulphides favor the altered fragments, often as minute veinlets or clusters of tiny crystals marginal to the quartz-carbonate stringers.

The pyrite is very fine-grained; individual grains range in size from .001 to .3 mm. with an average size of about .025 mm. The pyrite is essentially free from fracturing and all of it in the ore zones contains gold.

The arsenopyrite is extremely fine-grained, averaging .003 mm., and occurs in a similar manner to the pyrite but in more diversified habits. The most common type is of rhombic shape, with skeletal crystals fairly abundant, and columnar and dendritic aggregates occasionally noted. It is apparently younger than the pyrite as in places it contains inclusions of this mineral.

Like the pyrite the arsenopyrite carries gold, but tests indicate that not all of it is auriferous. Where the arsenopyrite is of skeletal or dendritic habit the ore is unusually rich in contrast to some of the rhombic crystals which are apparently barren.

Metallurgical tests and microscopic examination of concentrates show that about 35 per cent of the gold in the Beattie ore is in the free state. The remaining 65 per cent is intimately associated with the pyrite and arsenopyrite. The gold content is low, averaging less than 0.15 ounces per ton, and microscopic examination of the concentrates shows that the free gold particles range in size from 0.002 to 0.05 mm.

GENETIC CLASSIFICATION.

The structure and mineralogy of the Beattie ore deposit is unusual, particularly when compared with other gold deposits in northern Ontario and Quebec.

By far the largest proportion of the ore is a breccia of altered and bleached tuffs cemented by a network of fine-grained quartz and carbonate stringers, mineralized with auriferous pyrite and arsenopyrite. This, together with only minor amounts of mineralized schist, suggests that the deposit formed under relatively light load.

Striking features of the deposit are: (1) The alteration of the syenite porphyry and surrounding Keewatin rocks by solutions which bleached and feldspathized the Keewatin members with the apparent introduction of orthoclase in the "gray massive"; (2) the peculiar orthoclase "dikes" in the breccia ore; (3) the absence of pyrrhotite and other high-temperature minerals, and the presence of essentially only two simple sulphides, fine pyrite and arsenopyrite, the latter in minor amount.

These features and the structural aspects of the orebodies suggest that they should be classed as mesothermal or even epithermal.

MINING AND METALLURGY.

The Beattie ore deposits, owing to the strong wall rocks, the massive character of most of the ore and the relatively shallow depths so far reached, are mined largely by open stope methods.

The North or main orebody is extracted by a combination of open-pit and spiral stoping systems. The spiral stoping system requires a minimum of preliminary development, and this method as applied at the Beattie mine has been described by Mr. Jay Tuttle, the present mine manager.[6]

Early tests of the ore showed it to be of a particularly refractory nature. The present metallurgical practice was gradually developed during the early years of operations and has reached a high recovery level, considering the character of the ore. To summarize very briefly, the procedure is as follows: All of the ore is ground to 40 per cent minus 200 mesh, and flotation concentrates produced are treated in the roasting plant and the roasted residue is cyanided.

[6] Tuttle, J.: Spiral stoping at Beattie. Can. Min. Met. Bull., February, pp. 95–122, 1939.

HIGH-ALUMINA CLAYS OF PENNSYLVANIA[1]

RICHARD M. FOOSE.

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ABSTRACT.

More than five million tons of high-alumina clays occur in the Curwensville and Morgan Run districts of Clearfield County, Pennsylvania. These clays, associated chiefly with the Mercer member of the Pottsville group (Pennsylvanian), are flint, and diaspore-bearing flint clays. All

[1] Published by permission of the State Geologist of Pennsylvania. Presented before the Society of Economic Geologists, at its annual meeting, held in conjunction with the A. I. M. E. at New York, February, 1944.

gradations between flint clay and nearly pure diaspore occur at the Mercer horizon.

The stratigraphic position of the nodule (diaspore-bearing) clays is now shown to be only at the base of the Mercer. Consequently a datum plane now exists in the economically important Pottsville rocks where formerly structural mapping depended on the Homewood sandstone, commonly lacking, or the overlying Lower Kittanning coal of the Allegheny group.

The northeast-southwest trending Laurel Hill and Chestnut Ridge anticlines are the major structural features of the two districts. Normal faulting occurs in the Morgan Run district.

The clay occurs in lenticular masses which have wide ranges of thickness. Both the thickness and sporadic distribution of the clay bodies are apparently influenced by the underlying eroded surface of the Connoquenessing sandstone.

From the field relations and the petrographic textures and structures it is shown that the diaspore-clays were formed partly by the leaching of silica from flint clay and partly by addition of alumina to the flint clay.

INTRODUCTION.

FIRE clays have been economically important as the raw material for manufacturing refractory brick and other refractory products for many years. Until the beginning of the present world war, in 1939, little or no interest was expressed in these clays as a possible source of alumina, and of the metal aluminum. Since that time, however, and especially during 1941 and 1942 when the country's known reserves of bauxite were seriously depleted, and when imports of bauxite nearly ceased, these clays have been the subject of many detailed investigations. Recent studies of high-alumina clays in Pennsylvania indicate the presence of millions of tons of potential aluminum "ore," containing more than 35 per cent Al_2O_3 and not suitable for refractory products.

High-alumina clay in Pennsylvania occurs north and west of the Allegheny Front associated with the rocks of the Coal Measures, and especially with the Mercer member of the Pottsville group. Deposits of flint and diaspore clay have been worked for more than 50 years in Cambria, Centre, Clarion, Clinton, Indiana, Jefferson, Somerset, and Westmoreland Counties, but chiefly in Clearfield County, where three large and several smaller companies mine the clay for refractory products. Approximately three-fourths of the refractory clay produced in Pennsylvania is mined from two districts in Clearfield County: The Morgan Run district and the Curwensville district.

Location and Importance of Districts.

The Morgan Run district lies about seven miles west of Philipsburg between the two small towns of West Decatur and Faunce (Fig. 1). It takes its name from the creek which flows north through the district, and is approximately 25 square miles in area. Macadam roads traverse most of the area, and the Pennsylvania and New York Central Railroads pass through West Decatur and Faunce respectively. Because this is part of the well-developed Clearfield County bituminous coal field, the area has long been an important district. Refractory flint clay has been produced here since the

latter part of the 19th century. Only during the past decade have the refractories companies begun to use important quantities of the diaspore-bearing clays in the district.

The Curwensville district takes its name from the town which lies along the southeastern edge of the important producing area. The district extends south to Lumber City, west to Grampian, northwest to Chestnut Grove, and northward along the gorge of Anderson Creek. The total area included is approximately 35 square miles. Fair macadam roads traverse the southern

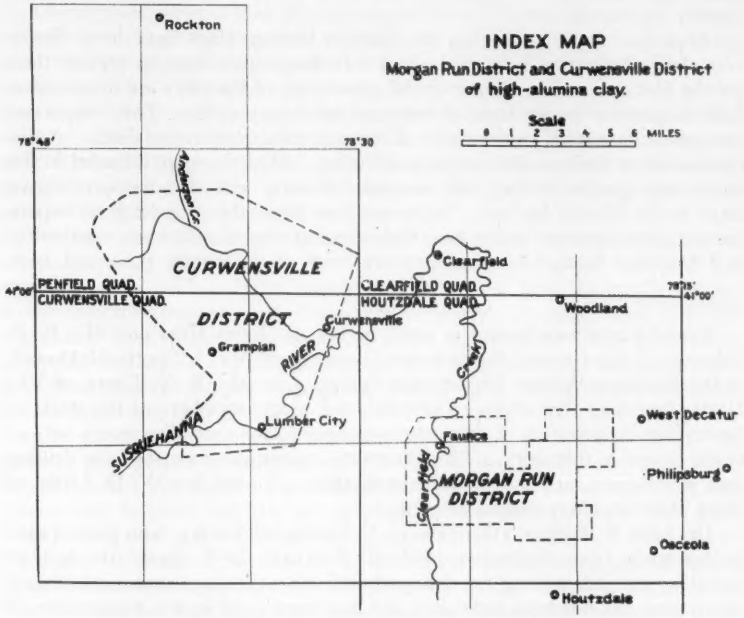

FIG. 1. Index map showing clay districts.

half of the district, and dirt and macadam roads the northern part. The Pennsylvania, Baltimore and Ohio, and New York Central Railroads all pass through Curwensville. The mining of bituminous coal is still an important industry in the district, and high-grade refractory clay has been produced since before 1900. As in the Morgan Run district, until recently it was the practice to gob in the mines or dump on the waste piles most of the diaspore-bearing nodule clays.

Purpose and Scope of Work.

The clays of Clearfield County were first studied in detail about 1903 by George H. Ashley. Since then, and especially during the last 30 years, in-

vestigations of the mineral resources, including the clay deposits, of the Curwensville and Houtzdale quadrangles and adjoining areas have been made by several investigators,[2] chiefly Ashley. None of the former work considered the diaspore-bearing clays alone, or the fact that they were high-alumina clays. During the summer of 1942 a study of high-alumina clays in Pennsylvania was begun by the author for the Pennsylvania Topographic and Geologic Survey. From September 1942 till February 1943 the study was intensely pursued with the able cooperation of the U. S. Geological Survey. Since that time, the investigations have been continued by the Pennsylvania Survey.

Important facts concerning the diaspore-bearing clays have been discovered through these investigations, and it is the purpose here to present them for the first time. The character and occurrence of the clays are discussed as fully as possible on the basis of field and laboratory study. Their important stratigraphic relation to the rocks of the coal measures is explained. A discussion about their possible origin is included. Flint clays are included in this study only insofar as they are associated directly with the diaspore-bearing clays in the Mercer horizon. In a very true sense this is a progress report, for the investigations in the two high-alumina clay districts are continuing, and doubtless further work will clarify some of the results presented here.

Acknowledgments.

Grateful acknowledgment is made to Mr. R. Jones Hess and Mr. B. B. Johnson, of the General Refractories Company, to Mr. J. Spotts McDowell, of the Harbison-Walker Refractories Company, to Mr. R. T. Lantz, of The North American Refractories Company, and to the members of the staffs of the mining departments of these three companies for extending every service in the course of this work. The refractories companies furnished the drilling data which form the basis of the investigation. To the late W. D. Little, of West Decatur, many thanks are due.

Dr. John M. Parker, III, of the U. S. Geological Survey, who participated in this study from September 1942, till February 1943, shared the task of gathering and interpreting the data and with the writer prepared a confidental report that has not been published, but has been used in the preparation of this paper. Inevitably his valuable suggestions and ideas, as well as certain

[2] Hopkins, T. C.: Clays and clay industries of Pennsylvania (clays of western Pennsylvania). Appendix to the Annual Report of the Pennsylvania State College for 1897.

Ries, H.: The clays of the United States east of the Mississippi River. U. S. Geol. Surv. Prof. Pap. 11: 298 pp., 1903.

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Ashley, G. H.: Geology and mineral resources of the Curwensville quadrangle. Penna. Topog. and Geol. Surv. Atlas 75: 80–95, 1940.

Leighton, H.: Clay and shale resources in Pennsylvania. Penna. Topog. and Geol. Surv. Bull. M 23: 239 pp., 1941.

Ashley, G. H.: Geology and mineral resources of southeastern Clearfield County. In preparation, Penna. Topog. and Geol. Surv., 1944.

specific results, especially for the Curwensville district, are embodied in this present work. Dr. Victor T. Allen, also of the U. S. Geological Survey, was helpful with the first petrographic studies and, many of his ideas on the mineralogy and origin of the diaspore-bearing clays have been borne out by this investigation. Every phase of the laboratory investigation and the preparation of this paper has been aided by the faithful work of my wife.

GEOLOGY.

Stratigraphy.

The exposed rocks of both districts are all of the Pennsylvanian age. They include the rocks of the Pottsville and the overlying Allegheny group, ranging from the Connoquenessing sandstone to the Upper Kittanning (C') and, locally, the Lower Freeport (D) coal. Most of the section is sandy shale, with several thick sandstones, and an extremely variable number of coal beds [8] with associated underclays. The variability of the rocks is further shown by radical lateral changes in lithology. Massive beds of sandstone commonly change in short distances to sandy shales. This is further aggravated by extreme local thickening and thinning of beds.

For many years investigators have tried to correlate the coal beds and the associated rock members of the Pottsville and Lower Allegheny series in the bituminous coal fields. Mixed success and failure has been the result because of the radical variations in thickness and lithology. In most cases it seems impossible to accurately correlate the rocks between the Connoquenessing sandstone and the Lower Kittanning coal over long distances because similar conditions of sedimentation during that part of early Pennsylvanian time did not maintain over long distances.

The stratigraphic confusion attendant upon every investigation including rocks of this age has naturally affected the correlation of flint clay and plastic clay associated with the coals as underclays. Prior to this investigation it was erroneously believed that the nodule clays, locally associated with flint clay, were to be found at the Mercer, the Brookville, the Clarion, and even higher horizons. It seems perfectly clear at this time that all the so-called nodule clays—the diaspore-bearing clays—are limited to one horizon, the Mercer. This fact has far reaching importance, because the accurate relative correlation of rocks in many areas where nodule clays occur becomes possible. Furthermore, a datum plane for structural mapping now exists in the economically important rocks of the Pottsville group where formerly much of the mapping was dependent upon the Homewood sandstone, which is locally missing, or upon the Lower Kittanning coal, many feet above, and aloof, as it were, from the stratigraphic confusion beneath.

There is no attempt here to describe rocks stratigraphically above the Pottsville group further than listed in Table 1. Those in the Pottsville group are briefly described.

Connoquenessing Sandstone. At the base of the Pottsville group the Connoquenessing sandstone lies unconformably on red and green Mauch

[8] Foose, R. M.: Brookville coal at Brookville, Pennsylvania. Proc. Penna. Acad. of Sci.: 107–111, 1941.

TABLE 1.

GENERALIZED SECTION OF FORMATIONS IN CURWENSVILLE AND MORGAN RUN DISTRICTS, CLEARFIELD CO., PA.

	Curwensville District.	Morgan Run District.
	Feet.	
Pennsylvanian:		
Conemaugh group	?	
Allegheny group		
Freeport member—Upper Freeport (E) coal	3–6	
Upper Freeport soft clay	3–9	
Upper Freeport limestone	0–4	
Shale and sandstone	16–55	31–
Lower Freeport (D) coal	2–4	3–6
Lower Freeport soft clay	3–5	2–4
Shale and sandstone	40–50	50–70
Kittanning member		
Upper Kittanning (C′) coal	1–3	1–3
Upper Kittanning soft and flint clay	2–12	1–10
Sandy shale	45–70	25–40
Middle Kittanning (C) coal	1–3	1–3
Middle Kittanning soft clay	2–5	3–7
Sandy shale	45–55	45–55
Lower Kittanning (B) coal	2–4	2–5
Lower Kittanning soft and flint clay	2–20	2–15
Clarion member		
Sandstone or shale	40–45	50–60
Clarion (A′) coal	0–2	0–2
Clarion sandstone or shale	30–35	5–25
Brookville (A) coal	1–4	1–3
Pottsville series [4]		
Homewood sandstone (or shale)	40–80	15–50
Mercer shale	0–25	0–25
Mercer coal (s)	1–2	1–3
Mercer soft, flint and nodule clays	5–20	5–25
Connoquenessing sandstone (or shale)	5–100	0–100
Unconformity		
Mississippian:		
Mauch Chunk series		
Red, green, and drab shale and sandstone	?	?
	289–638	243–511

(Modified from Atlas of Pennsylvania, No. 75, Curwensville quadrangle, G. H. Ashley and F. G. Clapp, Penna. Topographic and Geologic Survey, 1940; and from drill hole sections of the General Refractories Co.)

Chunk shale and sandstone (Mississippian). It is a white, medium to coarse-grained, massively-bedded formation, commonly 50 to 65 feet thick. Locally it is more than 100 feet thick and in some places it is completely absent. The wide range in thickness is not entirely due to differential sedimentation on the eroded Mississippian surface. Detailed study of the relationship between the Connoquenessing sandstone and the overlying Mercer member indicates an erosional interval which modified the Conoquenessing surface prior to Mercer deposition. This factor doubtless influenced the thickness, and shape of some of the Mercer clay deposits.

[4] Revision of lower Pennsylvanian stratigraphic succession places the Clarion member in the Pottsville series and makes the Lower Kittanning coal the base of the Allegheny. Oral communication with Geo. H. Ashley, representing G. S. A. Comm. on Pennsylvanian, February 1944.

Mercer Member. The Mercer member is economically the most important of the Pottsville group. It consists mainly of thin-bedded shale and sandy shale, containing one, and in some places two or three, coal beds which range from three to thirty inches in thickness. Usually directly underlying the lowest, main coal bed there are commonly 5 to 20 feet of clay. The clay nearly always includes the plastic and flint varieties, the latter being overlain and underlain by the former. At many places in the two large districts nodule clay is associated with the flint clay; in some places it occurs alone with plastic clay. The clay usually rests directly upon the Connoquenessing sandstone.

The term "conglomerate clay" has been applied to the Mercer clay at many places. This terminology springs from the early belief of some operators that the flint and nodule clays were associated only with the Pottsville conglomerate formation. Although the exact horizon was not known, the general association was correct.

Homewood Sandstone. Overlying the Mercer member, the Homewood sandstone is a non-persistent, medium-grained, buff and gray sandstone. More massively bedded than the Connoquenessing sandstone, which it often closely resembles, it crops out prominently at many places and ranges from 40 to 80 feet in thickness. It is more persistent in the Curwensville district, lying about 25 feet above the Mercer clay, than it is in the Morgan Run district. In both districts, however, it may change to sandy shale or shale within a lateral distance of a quarter mile.

Structure.

The Pottsville rocks, which underlie the eastern part of the Allegheny plateau, have a low regional dip toward the northwest, usually less than 10 degrees. The major structures of the Clearfield County clay districts are the Laurel Hill anticline, which has a northeast-southwest trend through the center of the Houtzdale quadrangle, and the Chestnut Ridge anticline, having a similar trend through the northwest quarter of the Curwensville and southern third of the Penfield quadrangles. The Clearfield syncline lies between. The maximum structural relief is 1,100 feet within 5½ miles. Modifying the major structures are many irregular elongated domes and basins, many but not all of which have a northeast-southwest trend. Further modifying the folded structures, especially east and southeast of the Clearfield syncline, are numerous normal faults, some of considerable displacement, and the strike of most of these is transverse or oblique to the trends of the major folds.

The main producing areas of both clay districts are on and near the crests of the two major anticlines, and down the flanks toward the Clearfield syncline axis to about where the Mercer clay horizon descends below drainage level (Susquehanna River and Clearfield Creek). The association of the clay districts with the two major anticlinal structures probably has no more significance than the fact that the Mercer horizon has been made accessible to surface or near-surface operation, and consequently to more economic exploitation.

Curwensville District. In the Curwensville district the structural trend of the pre-Mercer surface is northeast-southwest from northeast of Curwensville to near Lumber City, conforming to the main trend of all structures in the Allegheny Plateau rocks (Fig. 2). The Mercer clay horizon lies at about 1,200 feet, nearly river level, between the two towns and rises at the average rate of 200 feet a mile toward the northwest, reaching an elevation of 2,200 feet along the crest of the Chestnut Ridge anticline about five miles

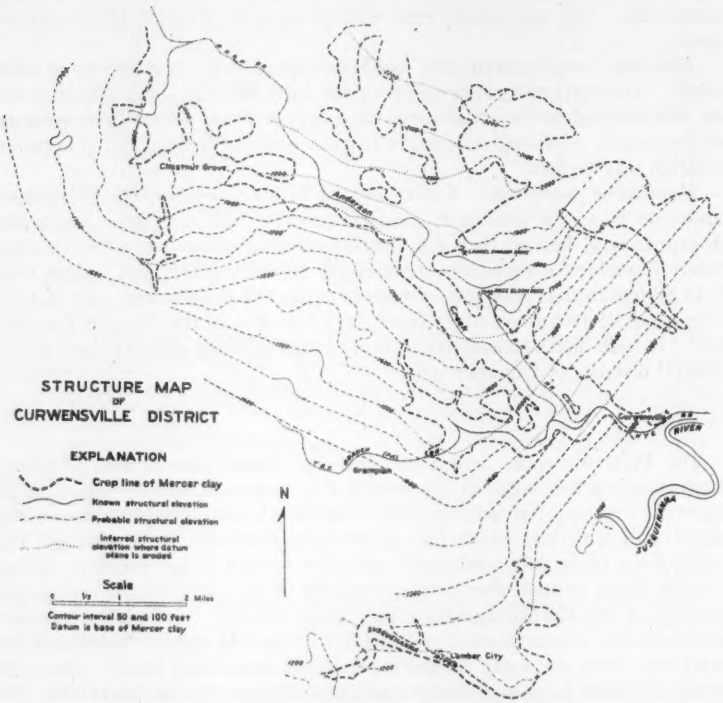

FIG. 2. Structure map of Curwensville district.

north and a little west of Curwensville. West of a north-south line through Lumber City the trend changes to west, northwest, and finally north, with a strong plunge of the formations toward the southwest along the axis of Chestnut Ridge anticline. Locally these trends are broken by minor warps which have made small domes and basins. Most of these are elongate. Although the long axis of most of them approaches parallelism with the major structures, this is not striking. The structure is relatively simple at all places in the district. There is no evidence of faulting beyond very small normal displacements in some of the mines.

Morgan Run District. The structure of the Morgan Run district is more complex. Faulting has largely influenced the structural trend of all the formations in the eastern part of the district, from Coal Run to Sanbourn and northeastward to Burly and toward West Decatur (Fig. 3). Four well-defined faults, and others not so well delineated, trend northwest-southeast and normally displace the formations downward on the southwest side. The largest, so-called Trojan fault, between Coal Run and Burly, has a displacement of up to 400 feet. There is some evidence that all the faults become smaller toward the northwest, eventually "hinging out." The southernmost

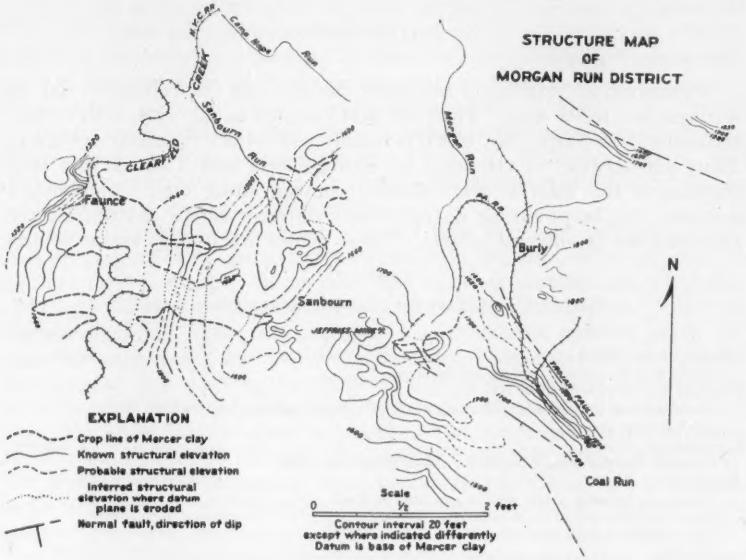

FIG. 3. Structure map of Morgan Run district.

fault clearly does this. The Mercer clay horizon, and all the formations in the faulted zone trend northwest-southeast, parallel to the faults, and the dips are steep. On the downthrow side of the Trojan fault near Coal Run the Mercer clay descends from an elevation of nearly 1,800 feet to less than 1,500 feet within a half mile.

The two faults southwest of the Trojan fault displace a well-developed anticlinal dome along its crest. The long axis of the dome lies in the line between Coal Run and Sanbourn. The southwestern flank of the dome probably represents the normal southwest plunge of the Laurel Hill anticline along its axis, and the northeastern flank of the dome was probably created by the relative downward displacement of all the rocks southwest of the Trojan fault. The northwest trend of the rocks along the southwest flank of the

dome is, therefore, comparable to similar trends in the Curwensville district where the plunging axis of the major structure cuts across the rocks. This is further borne out in the western part of the Morgan Run district where the rocks again strike northeast-southwest, along the northwest flank of the Laurel Hill anticline.

In the western part of the district local domes and basins modify the normal trend of the pre-Mercer surface. Some of these are clearly non-structural, indicating an erosional interval prior to Mercer sedimentation. In this part of the district the only evidence of faulting are minor normal displacements observed in the mines.

CLAY DEPOSITS.

Lithologic Description.

Two principal varieties of refractory clay and one non-refractory clay are distinguished in the area. These are flint clay and nodule clay, both of them refractory, and plastic clay, which is usually non-refractory, rarely refractory. Many sub-varieties of clay may be distinguished, and Table 2 lists these varieties in the order of their alumina content, citing their main physical features. In the producing districts many different names characterize certain varieties to different miners. These names are usually impressionistic

TABLE 2.

VARIETIES OF CLEARFIELD CO., PA., REFRACTORY CLAYS.

	Per Cent of Alumina.
"Burnt" nodule clay. Rusty brown, porous, cindery appearance.	70–75
Fine-grained (or blue) nodule clay. Homogeneous appearance; all small nodules. Finer grained and harder than green nodule clay.	60–65
Green nodule clay. Coarsely nodular, rough fracture. Usually greenish cast.	55 (approx.)
Nodule-block clay. Gradation between green nodule and flint or block clay. Nodules and nodular areas less than half of mass, scattered through block clay. Greenish. Fracture more blocky though still rough.	40–50
Spotted flint. Few scattered small nodules in flint clay. Fracture smooth conchoidal.	40–42
Flint clay. Very hard. Fracture smooth conchoidal with sharp edges and points. Ringing flinty noise under hammer blow. Weathers by breaking into smaller jagged fragments; never slacks down.	38
Block clay. Softer than flint clay. Fracture semi-conchoidal to irregular blocky. No ringing sound when struck. Weathers by crumbling into rounder granules than flint.	38
Semi-flint clay. Gradational from flint to soft plastic clay. Minor in amount. Hardness about same as block. Fracture rough and irregular, not very conchoidal.	35–37
Associated non-refractory clays include:	
Slabby soft clay. Fracture slabby and irregular. Slickensides very common.	30 (approx.)
Soft (Plastic) clay. Soft. Fracture very irregular. Chips and crumbles under little pressure. Slickensides common.	25–30
Shaly clay or clay shale. Bedding evident. Fracture shaly. Siliceous.	20–30

and frequently misleading. (The names in Table 2 are all names used in the districts, and they have been selected as type names because they best describe the lithology of the clay.) Although distinct features are listed for the clay varieties in Table 2, identification by visual examination is not easy. Often specimens of almost identical appearance may have widely variable alumina contents and be almost impossible to classify.

The three varieties of plastic clay in the Mercer horizon comprise by far the largest amount of clay in the two districts. Since the alumina content of these clays never amounts to 35 per cent, there will be no further specific discussion of them.

Flint clay is the most abundant type of refractory clay, although much of it is unsuitable as a refractory material. It is hard, usually has a gray or light buff color, has a smooth conchoidal fracture with very sharp edges and points, and will ring under the blow of a hammer. It resists weathering, eventually breaking into jagged fragments, never slacking down.

Block clay is similar to flint clay. It lacks the flinty character, however, and does not ring from a hammer blow. Block clay slacks down, being less resistant to weathering. It has the same alumina content as flint clay and is used extensively for refractory products.

Small irregular, rounded, and lenticular light gray and buff spots, most of them ranging from one to five millimeters in diameter, occur in some of the flint clay as primary structures. The spots, or nodules, are physically and chemically nearly the same as the matrix, although their porosity may be slightly different. There are also dark gray and black nodules, similar in shape and size, which are the mineral diaspore. These nodules of diaspore occur in flint clay in all degrees of concentration, so that there is a complete sequence from flint clay to "burnt" nodule clay, which is almost pure diaspore. An intermediate variety, called nodule-block clay, represents an almost equal distribution of about 35 per cent nodules in a 65 per cent matrix of flint clay. The alumina content of the clay increases according to the increase of nodules in the flint clay. As the nodules increase in amount, the color changes. Dark greenish-gray and rust-brown colors best characterize the nodule clays. There is usually more iron oxide present in the nodule clays than in the flint and associated clays. The average iron oxide content increases with increasing alumina, thus accounting for the predominance of rust colors. Five to ten per cent of iron oxide is common and nodule clays with 25 per cent are not unusual. In Table 3, representative analyses are presented for all the clay types. These analyses are of samples containing a minimum iron oxide content.

Occurrence of the Clay.

The clay deposits lie at the bottom of the Mercer member, under the lowest coal and usually on, or only a little above, the Connoquenessing sandstone. The flint and nodule clays are usually in the middle part of the clay horizon, being both underlain and overlain by plastic clay or shale or both. Commonly the clay at the top is very carbonaceous and "blocky," and that at the bottom is more sericitic and sandy.

TABLE 3.

REPRESENTATIVE ANALYSES OF CLAY TYPES.
Analyst—General Refractories Co.

Type Clay.	Ignition Loss.	Al_2O_3.	SiO_2.	Fe_2O_3.	K_2O+Na_2O.	TiO_2.	CaO.	MgO.	Total.
"Burnt" Nodule	14.40	75.72	4.00	2.17	.38	2.75	.10	.25	99.77
Fine-grained Nodule	13.88	61.52							
Green Nodule	13.50	54.50	26.76	.80	.95	2.26	.18	.30	99.25
Nodule-Block	13.46	49.94							
Flint	13.16	38.37	43.74	1.29	.96	1.72	.04	.28	99.56
Block	13.40	37.55	43.40	1.06	1.51	1.77	.13	.43	99.29
Semi-Flint	11.17	35.13	46.76	1.52	2.60	1.57	.18	.73	99.66
Slabby Soft	8.76	30.99	52.62	1.63	3.21	1.28	.30	.75	99.54
Plastic (soft)	8.09	27.40	56.84	1.82	2.99	1.28	.30	.91	99.63

Flint and nodule clay do not occur everywhere in the Mercer clay horizon. Their average thickness in the mines of the two districts is approximately six feet, but they range in thickness from 0 to 20 feet. Lateral variations in thickness may be rapid; in one case a bed of flint clay thinned from 13 feet to a mere trace within 100 feet. Locally the clay (including plastic clay) is cut out more abruptly by channelling. A detailed study of the thickness of the clay by isopach maps clearly shows the lenticular character and sporadic occurrence of the Mercer clay masses.

Nodule clay, when present, usually lies near the middle of the flint clay, into which it often grades through spotted flint clay. Nodule-block clay more commonly lies between flint clay and green nodule clay, and usually shows a transition from one to the other. This transition is sometimes gradual, sometimes rapid. Locally there is no transition, and green nodule clay lies directly on flint clay. "Burnt" nodule clay occurs as irregular masses and lenses in green and fine-grained nodule. The physical boundary between green nodule, fine-grained nodule, and "burnt" nodule is rarely distinct. These three varieties are in complex and confused relation with each other. "Burnt" and fine-grained nodule clays are enclosed almost everywhere *only* by green nodule clay, although one section records about six inches of "burnt" nodule between flint and block clay.

Green nodule and nodule-block clays are by far the most common of all the nodule clays. Fine-grained nodule is really a gradational type, and commonly bridges the physical gap between green and "burnt" nodule clay, though this is not always true. This variety is, therefore, similar to nodule-block clay in its physical occurrence.

A representative section of the Mercer clay is shown in Figure 4. Actual sections of the clay from diamond drill holes and active mines exhibit many variations from this representative section. In rare cases two beds of nodule clay occur, separated by a few feet of block clay. Locally, the presence of three to nine inches of coal separating flint, or flint and nodule clay has been observed. Lateral variation and gradation of the physical character of the clay itself is very common. An almost solid section of combined block and flint clay may change within 100 feet to a "representative" section, or even to

a dominantly nodule clay. Locally in both districts large thicknesses of nodule clay have been proved by drill holes within 100 or 200 feet of other drill holes showing "representative" sections.

Impurities consist principally of silica and iron. Silica, generally accompanied by sericite flakes, is most abundant toward the bottom of the clay. Iron is present as the oxide (chiefly limonite) and carbonate, finely disseminated throughout the clay (especially in "burnt" nodule clay) or con-

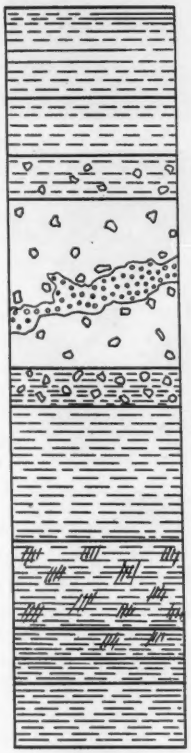
1'7" Dark shaly block
1'0" Dark gray block
9" Gray block with some nodule
3'0" Green nodule, bottom toward nodule block
including lens of "burnt" nodule
8" Nodule block
2'5" Gray block
1'6" Gray flint
6" Gray semi-flint
6" Gray block, a little slabby
1'3" Gray soft block

FIG. 4. Representative section of Mercer clay.

centrated as specks. Iron sulphide (pyrite or marcasite) occurs as specks ("shiners"), larger blebs up to one inch diameter, and thin veins ("slips"). Occasional veins of gypsum have been observed. Black, sub-round to irregular, dull splotches, usually on flint and block clay, are due to carbonaceous matter.

Areal Distribution of the Clay Deposits. The lateral variation in lithology and thickness of the clay has been described. Part of the variation, especially

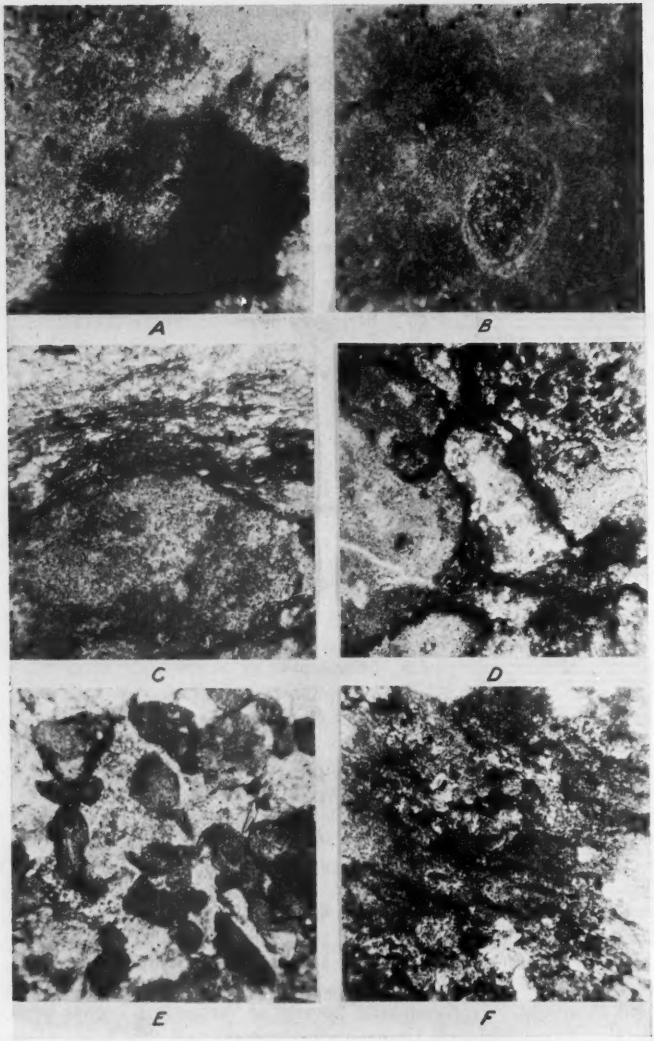

FIG. 5. Textures of six clay types. × 33.

A. Semi-flint or flint clay. Amorphous kaolinite. Black area, carbonaceous stain. Some black spots, iron oxide.
B. Spotted flint clay. Pellet of kaolinite in kaolinite groundmass.
C. Nodule-block clay. Nodule of diaspore (bottom) with kaolinite (above) oriented around it.

in thickness, is due to the erosional surface of the Connoquenessing sandstone on which the clay lies. Thicker parts of the clay very often lie in basin-like areas of the sandstone. In this way they are similar to certain Illinois [5] and Kentucky clays. Consequently, depressions in the pre-Mercer surface partially control the areal distribution of the lenticular deposits of clay.

Presumably there was some pattern of drainage on the pre-Mercer surface, and this pattern might influence the location of all the clay deposits. If the trend of the pattern were clearly known, it would aid in future prospecting. A considerable number of deposits have been mapped. Their shape and thickness are accurately known. There seem to be certain trends of occurrence, but no other conclusions can be stated at this stage of the work except that the deposits are irregular in shape, thickness, and areal distribution.

Relation of Nodule Clays to Structure. In the large Jeffries mine of the General Refractories Company near Sanbourn in the Morgan Run district, and in the Ross Bloom and Laurel Swamp mines of the North American Refractories Company, north of Curwensville, the relation of clay types to the structure were specifically noted. It was observed that nodule block and green nodule clay increased down the dip at the expense of spotted flint clay, which was more common where the clay had a higher elevation. In the Bloom and Jeffries mines, especially, this feature seems to be borne out. Certain drift faces, far removed from the main haulageway and 20 or 30 feet higher on the flank of the structure, show considerable spotted flint and very little nodule clay, whereas the converse is true farther down the flank in the main part of the mines.

Although there is no striking evidence to the contrary, until further detailed work in both districts has been completed, this relation will not be considered to hold throughout the entire area.

Petrographic Study of the Clay Textures and Structures.

Following are the results of petrographic study of the flint and nodule clays from the two districts. Only the major textural and structural features are described.

Semi-flint clay (Fig. 5A). Kaolinite constitutes almost 100 per cent of this type of clay. Nearly all the kaolinite occurs in an amorphous mass of lath-like, sheet-like, and finally "granular" material. Irregular areas of kaolinite appear darker than the rest for two reasons: Gray and black areas stained by carbonaceous material, and rust brown areas stained by iron oxide, usually a product of iron carbonate oxidation. Small black spots, which sometimes "freckle" considerable areas of both light and dark kaolinite, are, in most cases, also iron oxide.

[5] St. Clair, Stuart: Clay deposits near Mountain Glen, Union County, Illinois. Ill. Geol. Surv. Bull. 36: 71–83, 1916.

D. Green nodule clay. Nodules are all diaspore. Finer matrix is kaolinite. Black filling between nodules is iron oxide.
E. Fine-grained nodule clay. Nodules of diaspore in matrix of kaolinite.
F. "Burnt" nodule clay. Diaspore. Black areas are iron oxide. Increased porosity shown by white areas.

Thin (0.5 mm.) veinlets of pyrite cut across the kaolinite mass at some places. They are replacement veinlets, often in discontinuous segments with kaolinite between. A few anhedral grains of zircon and chlorite are present.

In one instance, petrographic examination of a clay megascopically classified as semi-flint showed a well-rounded nodule of diaspore. Around the nodule kaolinite closely conformed in a banded zone about 0.1 mm. wide (similar to Fig. 5C).

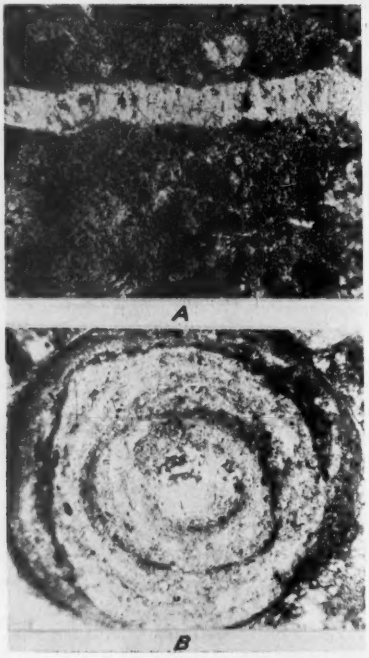

FIG. 6 A. Second generation diaspore veinlet cutting first generation diaspore. × 33.

B. Pellet of kaolinite completely replaced by diaspore. Note concentric structure. Kaolinite surrounds nodule. × 33.

Flint Clay. With the exception of rare anhedral grains of zircon, all the flint clays which were examined consisted entirely of kaolinite. The only significant difference between them and the semi-flint clays is one of uniformity in appearance. The kaolinite mass appears to have greater density and cohesion. A few basal plates of kaolinite were observed. Carbonaceous stains make irregular areas darker.

Spotted Flint Clay (Fig. 5B). The mineralogy of these clays is similar to the flint and semi-flint clays. Although illite was not identified in the lat-

ter, there probably was some. A few sheaf-like, sericitic-appearing masses of this mineral occur in the general kaolinitic ground mass of these clays.

Lenticular and nearly round areas of kaolinite, up to five millimeters in diameter, and possessing a vague concentric structure, as though they had been rolled, occur throughout the kaolinitic mass. A colloidal origin of these concentric structures is not precluded.[6] These, and areas of siderite of similar size make the clays "spotted." The siderite is commonly heavily masked by

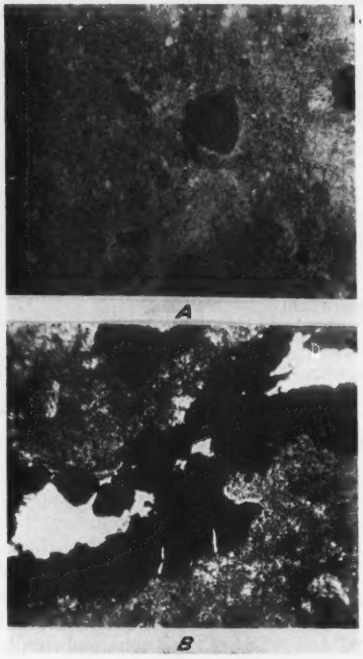

FIG. 7 A. Siderite, with serrate edges has replaced pellet of kaolinite in kaolinite matrix. Black area is iron oxide alteration. × 33.
B. Vein of pyrite (black) cutting across diaspore. Siderite (white) is earlier, but sometimes contemporaneous. × 33.

or completely altered to iron oxide. The siderite is secondary, having selectively replaced the kaolinite structures (Fig. 7A).

Nodule-block Clay (Fig. 5C). Kaolinite continues to be the amorphous-like groundmass. In the nodule-block clays it comprises between 45 and 95 per cent of the total clay. By comparison with megascopically examined

[6] Allen, V. T.: Mineral composition and origin of Missouri flint and diaspore clays. Mo. Geol. Surv. 5th Bien. Rept., App. IV: 17, 1935.
Mead, W. J.: Occurrence and origin of the bauxite deposits of Arkansas. ECON. GEOL. 10: 28–52, 1915.

specimens, it is suggested that when the kaolinitic groundmass comprises less than 45 per cent of the clay, the type no longer falls under the general nodule-block heading. It would probably be green nodule clay.

These clays show considerable diaspore. The diaspore irregularly replaces kaolinite as small veinlets and nodule-like masses (Figs. 6A and 6B). In addition to the diaspore veinlets, small veinlets of kaolinite cut older kaolinite. The older kaolinite in some places is clearly oriented around small areas of siderite. Its dark color in some places is due to staining by iron oxide, which also masks most of the siderite.

Green Nodule Clay (Fig. 5D). Kaolinite comprises between 15 and 45 per cent of the clay, serving as a matrix for the minerals diaspore, siderite, pyrite, and iron oxide. The kaolinite appears to be no different from its occurrence in flint clay. There is no orientation of the kaolinite. Two gen-

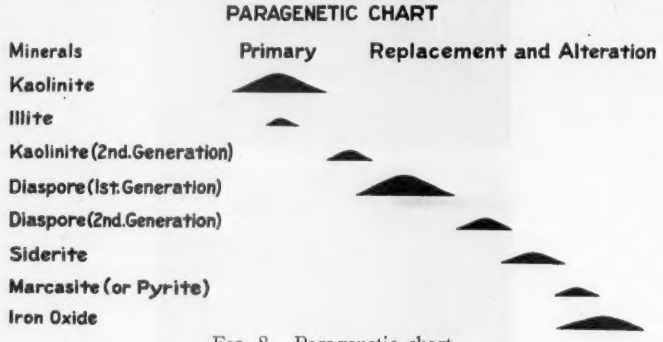

FIG. 8. Paragenetic chart.

erations of diaspore replace the kaolinite, the first of these as irregular nodular masses of all sizes, and the second as the veinlets which also cut across the first generation diaspore.

Considerable siderite, ranging up to 5 per cent of the clay at some places, replaces both kaolinite and diaspore, and commonly replaces the border contact between kaolinite and diaspore. Much of the siderite is masked by iron oxide.

These clays are more porous than any of the preceding clays. Although a general transition toward greater porosity could be noticed in the different types of clay, it is more clearly shown in this one.

Fine-grained Nodule Clay (Fig. 5E). Kaolinite is the matrix of this type clay, in which 70 to 90 per cent of the clay consists of diaspore. There is unusual uniformity in the size and rounded shape of the diaspore, which has replaced the kaolinite. At some places larger isolated masses of kaolinite are clearly being replaced. Again, second generation diaspore both replaces and "caps" first generation diaspore. Later siderite replaces both kaolinite and diaspore. Isolated subhedral grains of tourmaline and anhedral zircon are present.

Porosity in these clays is greater than in those previously described. Where there is no longer a matrix of kaolinite, and only diaspore, the porosity is greatest.

"Burnt" Nodule Clay (Fig. 5F). Kaolinite is nearly or completely absent. Only small and isolated patches remain between areas of diaspore which are replacing it. The diaspore, which comprises most of the clay consists of thousands of small, rounded "granules." There is considerable porosity in these masses, and especially between adjacent masses. Second generation diaspore cuts across the first. Sometimes it may represent as much as 15 per cent of all the diaspore. Siderite, which is later than both generations of diaspore, irregularly replaces it. Locally pyrite veinlets cut across everything, being later than siderite (Fig. 7B).

Paragenesis. From the study of the textural and structural relations of the clay types, the paragenetic relations of the different minerals are fairly clear (Fig. 8). Kaolinite is the chief primary mineral. At the time of its deposition a few detrital minerals, including zircon and tourmaline, were also deposited. The occurrence of illite is not prominent. It belongs to the general mass of kaolinite and is probably primary. Another generation of kaolinite is later, and cuts across the first. The first generation of diaspore may or may not be later than the second generation kaolinite. Second generation diaspore, as veinlets, replaces everything earlier. Siderite is contemporaneous with and later than the second generation diaspore. Marcasite (or pyrite) veinlets, and the development of iron oxide, are contemporaneous with some of the latest replacement by siderite.

Economic Factors.

Nodule clays were not considered desirable refractory clays by the companies which mined them for refractory products until about 1930. Prior to that time some nodule clays undoubtedly were used, but most of it was gobbed in the mines or dumped on rock dumps. The value of the nodule clays as highly refractory clays generally became known and they have since been used in increasing amounts for the manufacture of special refractory brick and for high-temperature refractory cements. The results of this work should have considerable value to the various companies using the nodule clays for refractory products, for their occurrence has never been described before, and the total known reserves of nodule clays have never been computed prior to this study.

Diaspore and diaspore-bearing clays have been used as a raw material for production of aluminum. This work has outlined large areas of diaspore-bearing clays which have too much iron to allow their use for refractory products. These high-iron, high-alumina clays may, therefore, be a potentially valuable source of aluminum ore.

More than five million tons of high-iron, high-alumina clay have been proved in the two districts. A much larger amount of probable "ore" has been indicated. This tonnage concerns only the clay which is unsuited for refractory products because of the high iron content. Most of the high-iron, high-alumina clay underlies unmined areas adjacent to active or abandoned

mines in the two districts. Large quantities are mined, however, and thrown on the dumps or gobbed in the mines.

ORIGIN OF THE CLAY.

Preliminary Considerations.

It is clear that the Mercer plastic and flint clays are of sedimentary origin, but the high-alumina nodule clays which are associated with them are not. No field relations indicate any disconformity between the flint and nodule clays. The diaspore, which comprises most of the alumina present in the nodule clays, is secondary. Porosity of the clays increases with an increasing percentage of alumina. Petrographic studies also show this. Chemical analyses show a corresponding decrease in silica. Most of the first generation diaspore in the nodule clays appears to represent concentration of alumina by the leaching of silica from the kaolinite. Second generation diaspore, which is definitely younger than the first generation, and which partly fills interstices, apparently has been introduced into the clay.

The small nodules of kaolinite in the kaolinite matrix of the spotted flint clays have been changed to diaspore before any part of the matrix itself has undergone change. Therefore, primary structures in the clay served as loci for the first development of diaspore. It has already been pointed out that the spotted flint clays give way to nodule clays down the dip of structures.

Theory.

From the evidence of the field and laboratory studies which has been described, the following geologic history and theory of origin seem to best explain all the facts:

A period of erosion followed the deposition of the Connoquenessing sandstone, creating an irregular surface with channels, basins, and domes. Shallow inundation followed, and in quiet waters fine kaolinitic material slowly settled. Some organic (carbonaceous) matter also settled with the kaolinite. At one or several stages during this quiet deposition, local conditions caused small kaolinite pellets to form, these being embodied in the general sediment. Toward the end of this stage, locally the sediments were bedded, later forming shale. Gradual emergence ended this stage of sedimentation and was followed by a short period of erosion.

The entire area was then barely submerged and lush vegetation accumulated, later forming the Lower Mercer coal. Post-dating the emergence which ended the second stage of deposition, probably during Pottsville time but very possibly later, the rocks were warped by dynamic stresses. The Mercer clay and the overlying coal were folded and only locally lay in horizontal position.

Surface water which passed through the coal and the shale rocks which lay between the coal and the clay probably dissolved sufficient alkalies from them to facilitate the leaching of silica in the underlying clay which it permeated. These waters slowly passed through the upper, more impure, less dense, part of the clay, eventually reaching the "middle" part and acting upon

the pellets of kaolinite and later the kaolinite matrix, leaching their silica.[7] Because the clay dipped gently, the waters migrated in the direction of the dip and caused greater concentration of alumina by the leaching of silica in that direction.

Later, water bearing alumina, which was probably leached from the upper block clays, deposited that alumina as a second generation of diaspore in the nodule horizon, partly filling interstices made by the prior leaching of silica, and thus "capping" first generation diaspore, and partly replacing first generation diaspore. As the porosity of the clay increased during the leaching process, the water had more freedom of movement, and consequently the development of nodule clays was enhanced. Later the porosity decreased as alumina was actually added to the clay instead of just being concentrated, and as iron carbonate and iron oxide were precipitated in the interstitial spaces. As previously indicated, iron oxide and carbonate are most abundant toward the top of the nodule clays.

There is little field evidence at this time to indicate what became of all the leached silica. Drill holes show very siliceous clay in small areas of both districts, and the bottom part of the clay horizon almost everywhere is higher in silica than the top. Possibly most of it escaped to the surface over a long period of time and was eroded away, but that is only a speculation.

HARRISBURG, PENNSYLVANIA,
March 31, 1944.

[7] Allen, V. T.: op. cit.: pp. 17–21, 1935.

THE HYDROTHERMAL ALTERATION OF FELDSPARS IN ACID SOLUTIONS BETWEEN 300° AND 400° C.

JOHN W. GRUNER.

ABSTRACT.

About 30 experiments, largely with feldspars, were made in HCl solutions at 300° to 400° C. (one at 525° C.). The concentrations of K and Al were varied to some extent. It was found that kaolinite forms only below 350° ± 10° C. and muscovite above this temperature to as high as 525° C. Pyrophyllite may form over the whole range from 300° to 525° C. though it may be only metastable below 350° C. K feldspars are metastable (probably also Na feldspars) at 400° C. provided the concentrations of the corresponding alkalies are high. Some of these reactions take place at such low pressures that the presence of a liquid phase in the bombs is precluded. The writer has attempted to explain some of the reactions.

INTRODUCTION.

FIVE years ago the writer described [1] a number of experiments which showed that muscovite could be synthetized in HCl solutions at 400° C. provided an excess of K ions were present in the solutions. The term "solution" as used here includes the gaseous phase. At 300° C. muscovite was stable or metastable under these conditions but could not form at this temperature in HCl solutions. At 300° C. kaolinite formed even in the presence of a large excess of KCl.

In the present investigation the experiments were extended to the alteration of potash and soda feldspars. Schwarz and Trageser [2] had altered feldspars to kaolinite in 1.0 and 0.5N HCl solutions at about 330° C. and below this temperature. Later they [3] altered feldspar to pyrophyllite in the same kind of solution at temperatures from 400° to 530° C. It is not stated clearly whether they were able to make pyrophyllite from 320° to 400° C. or whether kaolinite only was their product in this range. According to their description they used autoclave bombs with a volume of 160 c.c. which they filled with 120 c.c. of liquid (80 c.c. solution + 40 c.c. water) which is a very high degree of filling and must have led to pressures far in excess of those ordinarily produced. It was reasoned in the present investigation that HCl solutions should sericitize feldspars around 400° C. provided the concentration of K ions were high enough. It will be shown that this is the case though Noll,[4] on the basis

[1] Gruner, J. W.: Formation and stability of muscovite in acid solutions at elevated temperatures. Am. Min. 24: 624–628, 1939.

[2] Schwarz, R., and Trageser, G.: Über die künstliche Umwandlung von Feldspat in Kaolin. Zeit. anorg. Chem. 215: 190–200, 1933.

[3] Schwarz, R., and Trageser, G.: Über die Synthese des Pyrophyllits. Zeit. anorg. Chem. 225: 142–150, 1935.

[4] Noll, W.: Über die Bildungsbedingungen von Kaolin, Montmorillonit, Sericit, Pyrophyllit und Analcim. Mineral. Petrog. Mitt. 48: 227, 1936.

of experiments, claimed that muscovite (sericite) does not form at 400° C. in acid solutions. It had been planned originally to extend the temperature range and the concentrations in the experiments listed below. In 1942, however, it became impossible to obtain new gold linings for the bombs. The writer, therefore, decided to publish the data, though incomplete, since it may be some time before the work can be resumed. He is indebted to Mr. Lynn Gardiner for much assistance and to the Graduate School of Minnesota for financial aid in carrying out the investigation.

EXPERIMENTS.

Gold-lined bombs, which have been described a number of times,[5] were used. These have a volume of 51 to 52 c.c. In all experiments they were filled with 18 to 25 c.c. of solution, depending upon the temperature to which they were to be raised. Taking into consideration the specific volume of water below the critical temperature the bombs were never completely filled with liquid at these temperatures. On account of the other constituents present the pressures of saturated water vapor alone were not reached, and the critical temperatures were somewhat higher. The air above the liquid was replaced by CO_2 at room temperature and atmospheric pressure. The bombs were heated in large electric muffle furnaces controlled by Leeds and Northrop recording potentiometers. The thermo-couples were as close to the bombs as possible. Maximum temperature fluctuations amounted to 5° C. ±. The considerable weights of the bombs should have minimized them inside.

The following materials were used in the experiments:

Two analyzed feldspars from unknown localities. They are the identical specimens that Armstrong [6] analyzed and used in his experiments on the hydrolysis of feldspars. Their composition is given in Table 1. They were ground to pass through 100 mesh.

TABLE 1.

ANALYSES OF FELDSPARS.

(L. C. Armstrong, analyst.)

	Microcline	Albite
	%	%
SiO_2	65.46	66.01
Al_2O_3	19.12	21.40
CaO	nil	1.74
Na_2O	3.51	10.27
K_2O	11.93	.56
Li_2O	n.d.	n.d.
Ignition	0.18	.27
Total	100.20	100.25

Microcline: Locality unknown. Grayish white cleavage fragments. Albite present in perthitic intergrowth; calculation of the norm indicates a composition of 70.6 per cent orthoclase and 29.4 per cent albite.

Albite: Locality unknown. Grayish white moonstone cleavage fragments; calculation of the norm indicates a composition of 86.8 per cent albite, 8.6 per cent anorthite, and 3.1 per cent orthodase.

[5] Gruner, J. W.: op. cit., p. 624.

[6] Armstrong, L. C.: Decomposition and alteration of feldspars and spodumene by water. Am. Min. 25: 813, 1940.

Aluminum hydroxide (Merk). This material is a white powder and gives an X-ray pattern of bayerite, $Al(OH)_3$, and contains 37 per cent H_2O. Theoretically it should have 34.6 per cent.

"Silicic acid" (C.P., Mallinckrodt). It is a powder and contains 10.36 per cent H_2O = approximately $SiO \cdot \frac{1}{2}H_2O$. It is amorphous under X-rays.

In all experiments, in which one of the feldspars was used, 200 mg. was put into the bomb unless stated otherwise. After completion of the experiments, the solutions were tested for their approximate hydrogen ion concentrations. In some experiments the SiO_2 content of the filtered solution as well as the resulting acidity were determined. SiO_2 was hydrofluorized and the acidity was obtained by titration with NaOH. The solid material in the bombs was washed carefully and then dried at about 50° C. The powders were X-rayed in precision cameras with radii of 57.3 mm. Unfiltered Fe radiation was used. Good, sharp patterns were obtained in most experiments described. There was no difficulty in recognizing the products except in two cases where weak pyrophyllite and boehmite patterns were superimposed.

Such a combination of patterns, if faint, could be mistaken for montmorillonite or sericite, as possibly happened in some of Norton's experiments.[7] His X-ray data are confusing, probably because the measurements were made with a camera of too small a radius (28.6 mm.). Also, the characteristic lines of the minerals which have a spacing of 7.0 Å or more were omitted in his data. The data were recalculated by the writer and it was found, for example, that Norton's conversion product of albite (Table 11, p. 14) which he calls beidellite, is probably pyrophyllite, if it can be identified at all. It is not clear to the writer how Norton[8] was able to identify as many as four minerals in one X-ray pattern when these minerals were as closely related as dickite and kaolinite.

No boehmite, AlO(OH), was reported in Norton's experiments though Noll[9] and the writer obtained this product frequently. Norton[10] reported gibbsite as end product from nephelite in one experiment. His data, however, agree much better with boehmite. The resulting confusion shows how important it is to use the proper X-ray technique in obtaining data for the identification of silicates and other minerals giving many and often diffuse lines.[11] Besides the 28 experiments which are tabulated in Tables 2, 3, and

[7] Norton, F. H.: Hydrothermal formation of clay minerals in the laboratory. Am. Min. 24: 1–17, 1939.

[8] Norton, F. H.: Hydrothermal formation of clay minerals in the laboratory, Part II. Am. Min. 26: 10, 1941.

[9] Noll, W.: op. cit., pp. 210–247.

[10] Norton, F. H.: op. cit., 1939, p. 14, Table 12.

[11] The reproductions of photographs or diagrams are rarely satisfactory. They do not show small but important differences that are brought out by actual measurements. On the other hand, tables with all the measurements are too expensive to print. If they are published, however, a definite system should be used. The interplanar spacings on the films should be converted to angstrom units in the tables and should not be given in sines or angles. The lines nearest the zero beam are very important and absolutely essential in recognizing minerals. Data without them have little value. If photographs or diagrams are reproduced they should also contain the interplanar spacings in angstrom units. The diagrams by Norton (op. cit., 1941, pp. 4 and 6) are not usable because they contain only a part of the necessary information.

Another point needs emphasis. The intensities of the lines of synthetic products and the corresponding natural minerals, particularly in layer silicates, may be very different due to

TABLE 2.

HYDROTHERMAL EXPERIMENTS AT 300° C. IN HCl SOLUTIONS.
Amount of mineral in each experiment 200 mg. Volume of bomb 52 c.c.

No.	Original Mineral	Grams KCl*	Grams $Al(OH)_3$	Original Acidity	Resulting Acidity	pH after Experiment	Time in Days	Pt. p. Million SiO_2 in Solution	Conversion Product	c.c. of Solution	
										At Start	Recovered
158	microcline	1.0	—	0.105 N	0.086	About 1	10	n.d.	pyrophyllite (poor diagram)	25	25
162	microcline	1.0	—	0.105 N	n.d.	About 1	17	1530	pyrophyllite	25	25
160	microcline	—	—	0.105 N	0.076	About 1	8	n.d.	pyrophyllite	25	25**
168	microcline	1.0	0.1	0.105 N	0.064	About 2	13	1028	kaolinite, some boehmite	25	21
163	soda feldspar	1.0	—	0.105 N	0.067	About 1–2	17	1333	pyrophyllite	25	21
173	soda feldspar	—	—	0.105 N	n.d.	About 1	17	n.d.	pyrophyllite and some kaolinite	25	22
169	soda feldspar	1.0	0.1	0.105 N	0.004	About 4	13	570	kaolinite, some boehmite	25	10

* The normality with respect to KCl would vary depending upon the amount of solution left toward the end of the experiment.
** Much gold in yellow solution.

TABLE 3.

HYDROTHERMAL EXPERIMENTS AT 400° C. IN HCl SOLUTIONS AND IN WATER.
Amount of mineral 200 mg. Volume of bomb 52 c.c.

No.	Original Mineral	Grams KCl*	Grams $Al(OH)_3$	Original Acidity	Resulting Acidity	pH after Experiment	Time in Days	Pt. p. Million SiO_2 in Solution	Conversion Product	c.c. of Solution	
										At Start	Recovered
161	microcline	—	—	0.105 N	0.078	About 1	9	n.d.	pyrophyllite, and microcline left	18	13
159	microcline	1.0	—	0.105 N	.089	About 1	9	n.d.	microcline	20	20**
171	microcline	1.0	—	0.105 N	n.d.	About 1	16	n.d.	microcline	20	5
166	microcline	1.0	0.100	0.105 N	n.d.	About 1	7	n.d.	muscovite, some feldspar left	20	8
178	soda feldspar	—	—	0.105 N		About 1	14	n.d.	pyrophyllite, some feldspar left	18	18
164	soda feldspar	1.0	—	0.105 N	0.082	About 1	7	1600	pyrophyllite, some feldspar left	20	20
179	soda feldspar	—	0.100	0.105 N		About 1	12		pyrophyllite and boehmite, some feldspar left	18	moist
165	soda feldspar	1.0	0.100	0.105 N	0.053	About 1	7	736	muscovite	20	20
175	soda feldspar	0.5	0.100	0.105 N			13		muscovite	20	moist
183	soda feldspar	0.5	0.100	0.350	n.d.	About 1	8	470	muscovite	15	12
177	soda feldspar	0.5	0.100	water			16		muscovite, some feldspar left	20	dry
182	soda feldspar	0.5	0.100	water			17		muscovite and some boehmite, some feldspar left	18	moist
180	soda feldspar	NaCl 0.5	—	0.105		About 1	16	n.d.	soda feldspar and pyrophyllite	18	10

* See footnote, Table 2. ** Much gold in yellow solution

TABLE 4.

HYDROTHERMAL EXPERIMENTS IN HCl SOLUTIONS BETWEEN 340° AND 525° C.
Volume of bomb 50 c.c.

No.	Material Placed in Bomb	Original Acidity	Resulting Acidity	pH after Experiment	Time in Days	Conversion Product	c.c. of Solution		Temp. in C.
							At Start	Recovered	
170	.058 g $Al(OH)_3$ .148 $SiO_2 \cdot \frac{1}{2}H_2O$ 1.000 KCl	0.105 N	0.081	About 1	9	muscovite and some boehmite	18	18	400°
181	.090 g $Al(OH)_3$ .153 $SiO_2 \cdot \frac{1}{2}H_2O$	0.105		About 1	10	pyrophyllite	18	17	400°
184	.227 g $Al(OH)_3$ .201 $SiO_2 \cdot \frac{1}{2}H_2O$ .500 KCl	0.105		About 1	10	pyrophyllite and boehmite	18	18	360°
186	as in No. 184 but 2.00 g KCl	0.105		About 4	10	muscovite	18	18	360°
189	as in No. 184 but 1.00 g KCl	0.105		About 1	12	muscovite and some boehmite	18	17	360°
187	as in No. 186	0.105			16	boehmite	18	moist	340°
188	as in No. 189	0.105		About 1	10	pyrophyllite and boehmite	18	18	340°
174	.200 g soda feldspar .100 $Al(OH)_3$ .500 KCl	0.105		About 1	1	muscovite	25	½	525°

4, a number of others were made which were only partially successful due to some failures in the apparatus. In two of these the gold discs on the top of the bombs had been "eaten through" with the result that much iron had been dissolved, and crystals of magnetite had formed. The dissolving of gold from the linings of the bombs, while not a part of the problem, is worth mentioning. In experiments 159 and 160 much gold was found in the solutions, which were of a yellow color. On standing, this gold was slowly precipitated as a brownish deposit. Why other very similar solutions were colorless and contained no gold is not understood. There was, however, evidence that gold recrystallized in dodecahedrons in some of the other experiments, presumably by going into solution and crystallizing out probably almost immediately. In unpublished experiments in which $MgCl_2$ was used with HCl solutions the amount of gold "transfer" in this manner was quite remarkable.

some preferred orientation of the larger particles of the natural material though the interplanar spacings are exactly the same. Most conspicuous examples of this kind are pyrophyllite and muscovite. The few lines of montmorillonite agree with lines of pyrophyllite except for (001) near the zero beam. Therefore, great care must be exercised in comparing films.

* See footnote, Table 2. ** Much gold in yellow solution

This behavior may suggest a reason for the common association of gold with the chlorite and mica groups.

In some of the experiments only a part of the original solution was recovered. The leakage must have occurred early in the heating. If the top of the bomb was not screwed on tight enough the solutions could have partially escaped before the copper washer and gold collar of the bomb had expanded sufficiently to stop the leak. Though practically all the solutions had escaped in experiments 179, 175, and 177, the results are exactly what one would have expected if the solutions had been still present. They were gone when the bombs were removed from the furnace as could easily be ascertained by shaking the bombs, and, therefore, leakage was not due to cooling. In the experiments of Table 2, the pressures were probably between 80 and 87 atm., depending upon the salts in solution. In those of Table 3 the pressures were between 250 and 350 atm., except in those cases in which the solutions were largely lost.

DISCUSSION OF RESULTS.

Exclusive of boehmite AlO(OH), which is a dimorph of diaspore, we deal with only five minerals in our experiments. They are:

K feldspar	K Al Si_3O_8,	K : Al : Si = 1 : 1 : 3
Na feldspar	Na Al Si_3O_8,	K : Al : Si = 0 : 1 : 3
pyrophyllite	$(OH)_2$ Al_2 Si_4O_{10},	K : Al : Si = 0 : 1 : 2
muscovite	$(OH)_2K$ Al_3 Si_3O_{10},	K : Al : Si = 1 : 3 : 3
kaolinite	$(OH)_8$ Al_4 Si_4O_{10},	K : Al : Si = 0 : 1 : 1.

They seem to be the only ones which can exist in the solutions tried, and which form in the temperature range between 300° and 525° C. Quartz, of course, would be stable but it is formed in none of the experiments. The writer, so far, has obtained quartz only in experiments in which talc was treated with 0.175 N or stronger HCl solutions at 300° C. in which talc is completely soluble. Evidently saturation was reached in these solutions with respect to SiO_2. Mg ions, evidently, are not capable of combining with SiO_4 groups to form new Mg silicates in acid solutions. Al and SiO_4 ions, on the other hand, can produce insoluble and stable compounds. The SiO_4 ions are, therefore, withdrawn from solution sufficiently rapidly that they cannot reach the saturation point necessary for the formation of quartz. This statement is based on the belief that quartz does not form directly from colloidal solutions of SiO_2 but that mineralizers are necessary which cause SiO_2 to ionize, the SiO_4 groups then forming quartz in either acid or basic environments.

The end products in acid solutions should be different from those of neutral or basic ones whenever the acid is capable of leaching large amounts of a constituent and holding them in solution. This happens to the alkalies of the feldspars which can be taken into solution as long as the acidity is maintained and their concentration does not exceed a certain maximum. This explains the formation of pyrophyllite from microcline in experiment 160, Table 2. The reaction takes place according to equation (1).

$$2KAlSi_3O_8 + 2HCl \rightarrow (OH)_2Al_2Si_4O_{10} + 2SiO_2 + 2KCl \qquad (1)$$

Even in experiments 158, 162, and 163 in the presence of a relatively large K ion concentration, this reaction proceeds from left to right. It demonstrates that no potassium silicate can form at 300° C. in acid solutions though some have been synthetized in neutral and basic ones, as, for example, muscovite and leucite.

It was stated by Noll [12] that pyrophyllite could not form much below 400° C., and the writer had been of the same opinion, basing it on his earlier experiments [13] in which only kaolinite was obtained at 300°. In Table 2, it is seen, however, that pyrophyllite forms at 300° C., if the concentration of Al ions is low at any given time. If it is considerable, as in 168 and 169, kaolinite will form and any Al in excess will become boehmite, AlO(OH). The reaction is expressed by equation (2)

$$KAlSi_3O_8 + Al(OH)_3 + HCl \rightarrow (OH)_4Al_2Si_2O_5 + SiO_2 + KCl \quad (2)$$

in which free silica appears on the right or by equation (3)

$$2KAlSi_3O_8 + 4Al(OH)_3 + 2HCl \rightarrow 3(OH)_4Al_2Si_2O_5 + 2KCl + H_2O \quad (3)$$

in which all SiO_2 is needed for the kaolinite. One tenth of a gram of $Al(OH)_3$, which was added in experiments of Table 2 and 3, would have been just about enough to convert 0.2 grams of microcline to muscovite or kaolinite if all the SiO_2 had been used up in the reactions. Therefore, equation (2) is the more likely reaction in our experiments because boehmite is a by-product.

In the natural alteration of feldspars the formation of pyrophyllite seems to be rare, probably because there is usually much Al available. It has been reported by Buddington [14] and Clapp [15] as an alteration product of feldspars. There exists a possibility that it has been mistaken for sericite in some instances, as the two minerals resemble each other under the microscope.

Table 3 shows clearly how the products of the alteration depend on the respective concentrations of K and Al when the experiments are made under the same conditions otherwise. In experiments 161 and 178 the feldspars will alter to pyrophyllite provided the concentrations of K are not much greater than the amounts that can be leached from the feldspars. This had also been demonstrated earlier by Schwarz and Trageser [16] for the same temperature of 400° C.

If the K ion concentration is materially increased, without adding $Al(OH)_3$, no alteration seems to take place as shown in experiments 159 and 171. Potash feldspar may be metastable under these conditions though it does not form as shown in experiment 170, Table 4, in which the proper proportions of $Al(OH)_3$ and SiO_2 to make feldspar combine to muscovite. Ex-

[12] Noll, W.: op. cit.

[13] Op. cit., p. 627.

[14] Buddington, A. F.: Pyrophyllitization, pinitization and silicification of rocks around Conception Bay, Newfoundland. Jour. Geol. 24: 130, 1916.

[15] Clapp, C. H.: Alunite and pyrophyllite in Triassic and Jurassic volcanics at Kyoquot Sound, B. C. Econ Geol. 10: 70, 1915.

[16] Zeitsch. anorg. Chem. 225: 142, 1935.

periment 180 indicates a similar stability for soda feldspar provided the Na ion concentration is high.

Experiment 164 is significant because it shows that no simple exchange of Na for K ions takes place though the K ions are quite concentrated. This statement needs modification for O'Neill [17] working with the writer found that potash feldspar, adularia, will form from soda feldspar provided the K ion concentration is high and the solution is not more acid than about 0.001 N. This simple base exchange is also reversible.

Theoretically muscovite can form from feldspars in a number of ways as shown by equations (4), (5), (6), and (7).

$$3KAlSi_3O_8 + 2HCl \leftrightarrows (OH)_2KAl_3Si_3O_{10} + 6SiO_2 + 2KCl \quad (4)$$

$$3NaAlSi_3O_8 + 2HCl + KCl \leftrightarrows (OH)_2KAl_3Si_3O_{10} + 6SiO_2 + 3NaCl \quad (5)$$

$$KAlSi_3O_8 + 2Al(OH)_3 \leftrightarrows (OH)_2KAl_3Si_3O_{10} + 2H_2O \quad (6)$$

$$NaAlSi_3O_8 + 2Al(OH)_3 + KCl \leftrightarrows (OH_2KAl_3Si_3O_{10} + 2H_2O + NaCl \quad (7)$$

In the experiments 166, 165, 175, and 183 muscovite was produced, but an excess of Al and K ions was necessary. Which of the four reactions were involved is difficult to decide. Reactions (4) and (6), or (5) and (7) could occur more or less simultaneously depending upon the concentrations and acidities. It should be noted that the acidity in experiment 183 was as high as 0.35 N. On the other hand, the same results were obtained in experiments 177 and 182 in which the solutions were neutral.

It will be observed that in some experiments small portions of the feldspar remained unaltered. The reason for this incomplete reaction may be that equilibrium was reached. It is more likely, however, that the time was too short for the coarser grains to become altered. That the unchanged grains were coarse (about 100 mesh) could be seen in the X-ray powder photographs, for the lines of the feldspar pattern consisted of discontinuous dots and dashes. This is always a sign of coarseness of grain, especially if the powders are rotated in the cameras as they were.

Some of the experiments of Table 4 were made for the purpose of establishing more closely the point above which kaolinite is not stable and below which muscovite will not form in acid solutions. In experiments 184, 186, 189, 187, and 188 the quantities of $Al(OH)_3$ and $SiO \cdot \frac{1}{2}H_2O$ were proportional to those necessary to form muscovite. The concentrations of KCl varied between wide limits. These variations apparently account for pyrophyllite in experiment 184 and muscovite in experiment 189 at 360° C. An important fact is that kaolinite was not produced at 360° C. or above, and muscovite did not form at 340° C. or below. Therefore, the boundary between the fields of formation of the two minerals lies somewhere between 340° and 360° C. for acidities in the neighborhood of 0.1 N. As the acidity decreases the field of formation of muscovite probably extends to lower temperatures but does not reach 300° C. at 0.05 N as shown in the earlier paper by the author.[18]

[17] O'Neill, T. F.: Unpublished Ph.D. Thesis.
[18] Op. cit., p. 627.

In experiment 170, $Al(OH)_3$ and SiO_2 were chosen in the proportions of potash feldspar though this mineral was not expected to form. Apparently the reaction was that of equation (4) for the product was muscovite and a little boehmite. In experiment 181 the proportions chosen were those of pyrophyllite, and this was the mineral which resulted.

The two experiments 187 and 172 are of interest because the pressures on account of leakage must have been low. In experiment 172 the temperature control had been accidentally shifted, and the bomb was at a low red heat. With ½ c.c. of solution it would be difficult to calculate the pressure under which this muscovite formed at 525° C. It must have been less than 36 atm. In experiment 187 the pressure evidently was not high enough to produce kaolinite or pyrophyllite. $Al(OH)_3$ was simply converted to the lower hydrate boehmite.

CONCLUSIONS.

The concept that the more volatile constituents of the magmas as they leave the crystallizing masses are acid in reaction, though they may change their characteristics as they move on, has become fairly well established in the last twenty years.[19] It is not necessary at this place to enter into extended discussions as Graton [20] has done as to the inadequacy of such acid solutions to produce ore deposits. It is also probably immaterial, at least in some cases, whether the acidity is produced by halogens or the SO_4 radical, since the pH of a solution is the more important factor. What matters in our investigation is that such solutions exist and that certain hydrothermal minerals may have been formed by them, or if not, may be stable in them, as should be demonstrable in the laboratory. K and Na feldspars were selected for the experimental study because they are not only formed by some hot solutions but even more readily altered. The temperature range was 300° to 400° C. except in one experiment. The acidity of the solutions was usually 0.1 N, though 0.35 N was tried with similar results. The following conclusions may be reached:

1. Kaolinite, pyrophyllite, muscovite (sericite), and boehmite are formed in acid solutions.

2. The feldspars themselves do not form but may be metastable.

3. The concentration of K ions and the ratio of Al to Si ions (or Al_2O_3 to SiO_2) determine which mineral will form and be stable at a given temperature.

4. Kaolinite will form from feldspars and is stable below approximately 350° ± 10° C., regardless of K ion concentration, provided the ratio of Al : Si is about 1 : 1. This means that additional easily available Al has to be in the system.

5. If this is not present pyrophyllite will form instead, since the ratio of Al : Si in pyrophyllite is 1 : 2, and in kaolinite it is 1 : 1.

6. Pyrophyllite will also form from feldspars from 350° C. upward to at least 530° C. The latter figure is by Schwarz and Trageser, who used 0.5 N

[19] For summaries see papers by N. L. Bowen, C. N. Fenner, and C. S. Ross in "Ore Deposits of the Western States," Lindgren Volume, A. I. M. E., 1933.

[20] Graton, L. C.: Nature of the ore-forming fluid. ECON. GEOL. 35: 197–358, 1940.

HCl solutions. The K ion concentration must not be much greater than the amount that the acid can remove from the K feldspar. Boehmite may form in such a solution if Al ions are present in excess of those required for pyrophyllite.

7. If K and Na ions respectively are high but no additional Al is available the feldspars remain unaltered. This is not a true stability though no alteration was noticed at 400° C. in 16 days. It is certain that no K feldspar can be synthetized at this temperature in acid solution. Muscovite or pyrophyllite will be the result even though the proportions chosen are those of K feldspar.

8. Muscovite will form readily from feldspars beginning at 350° ± 10° C. to 525° C., the highest temperature tried, provided both K and Al are in sufficient concentrations. This reaction occurs also in 0.35 N. HCl solution.

We know from the experiments of Noll [21] and those in Table 3 that muscovite also forms in neutral solutions at as low a temperature as 200° C. O'Neill [22] produced it in basic solutions which had a normality of 0.01 KOH. If the solutions are more basic, however, minerals like kaliophilite or leucite will result at 300° to 400° C. Under neutral or somewhat basic conditions the feldspars themselves may be stable and it is easy to change Na feldspar to adularia by simple base exchange according to O'Neill. This reaction is reversible.

In experiments made by Friedel, Doelter, Thugutt, Allen, Baur, Königsberger, Müller, Niggli, Morey, Fenner, and others,[23] muscovite was produced very rarely because the solutions were commonly so high in potash and sufficiently basic that kaliophillite, leucite, or orthoclase formed. Experimental facts point then to the presence of slightly basic to acid solutions as causes of sericitization.

The alteration of *individual feldspar crystals* to sericite is in the nature of leaching of SiO_2 and the simultaneous addition of Al_2O_3 and K_2O. If it were leaching only the mass would be reduced to one-half while the volume remained constant, a condition not observed in the field or under the microscope. It is not easy to account for the source of the added Al_2O_3 in either acid or slightly basic solutions. It could come from adjoining regions now completely silicified as has been advocated by some students of the problem.

In this case we would have simply a movement of SiO_2 out of the feldspathic areas toward the centers of silicification and of Al_2O_3 in the opposite direction. K ions would travel in the same direction as Al_2O_3. Al_2O_3 could be carried as $KAlO_2$ which has a basic reaction, or as $AlCl_3$ which is acid.

One finds the statement that carbonates which are frequently found in sericitized rocks would have been destroyed if the mica had formed in an acid environment. This would depend, of course, on the partial pressure of CO_2 in such a system, as well as the concentration of the metallic ions which usually are found in carbonates in hydrothermally altered rocks. It is conceivable that the reaction $CaCO_3 + 2HCl \rightarrow CaCl_2 + H_2CO_3$ proceeds from right to left if the pressure of CO_2 is very high.

[21] Noll, W.: op. cit.

[22] O'Neill, T. F.: Unpublished thesis, University of Minnesota.

[23] For abstracts see: Morey, G. W., and Ingerson, Earl: The pneumatolytic and hydrothermal alteration and synthesis of silicates. ECON. GEOL. 32: 607–761, 1937.

Evidently the vapor pressure of H_2O in some experiments in which there was leakage was not very high. Yet the results were essentially similar to those in which the pressure was that of saturated H_2O vapor. A liquid phase cannot have existed in the bomb and it is difficult to imagine by what process the SiO_2, Al_2O_3, and KCl moved at 400° C. The transfer of SiO_2 at such low pressures as a few atmospheres must be extremely slow, if it takes place at all.

The formation of new silicates from other solid phases like feldspars and $Al(OH)_3$ in this type of experiment is little understood. Does the feldspar dissociate hydrolytically in the solution with the resulting ions K^+, Al^{+++}, $SiO_4^{==}$, OH^- and H^+, and do the new insoluble compounds form from those ions? The degree of ionization must be extremely small in such a system particularly with respect to SiO_4 groups. The dissociation of the feldspar would not proceed any more rapidly than the precipitation of the new compound could take place. If it happens that two compounds as pyrophyllite and kaolinite, are stable or metastable at the same temperature of 300° C., and both are approximately equally insoluble, that one would probably form for which at this moment the ratio of Al to Si ions were just about correct. Let us assume that it were pyrophyllite. If by a later addition of Al ions the equilibrium were shifted in favor of kaolinite the first mineral would dissolve and kaolinite would be precipitated.

In a similar manner the metastability of microcline in experiments 159 and 171 can be explained. The addition of KCl, as can be seen in equation (4), would have a tendency to drive the reaction to the left, that is, prevent the dissociation of the microcline. On the other hand, in experiment 170, in which the compounds $Al(OH)_3$, SiO_2 and KCl were used, the first two in the proportion of K feldspar, muscovite resulted because this mineral is stable and it was not necessary to dissolve first another metastable one as a source of supply.

It is hoped that this investigation can be resumed after the war and those points attacked which still need explanation.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINNESOTA,
June 24, 1944.

PHOTOMICROGRAPHY BY COMBINED TRANSMITTED AND REFLECTED LIGHT.[1]

ERNEST E. FAIRBANKS.[2]

ABSTRACT.

Important textural relationships of oolitic iron ore minerals that contain both transparent and opaque areas are difficult to show by any conventional photographic method. However, entirely satisfactory photomicrographs were obtained by a simple arrangement new to the writer. This arrangement consisted of a combination of both transmitted and reflected light to illuminate a polished thin section. This method reveals the detailed structure of an oolite and that of its nucleus. The extent of replacement changes may be determined. Important genetic relations of oolite, stromatolith, non-oolitic constitutents, and other hematite-bearing materials can be distinguished and photographed. An advantage is found in the reduction of the total number of required photomicrographs.

THE accompanying photomicrographs of a polished thin section were made with an ordinary Huygenian eyepiece and noncorrected objectives. If possible, objectives should be used which have been corrected for proper tube length and use without cover glass. This is important with magnifications exceeding 90 times. Filters can be used independently for either transmitted or reflected light component. Similar results are theoretically possible with this twofold illumination of ordinary thin sections by photographing with the aid of objectives having coated lenses,[3] but these were not used. Fairly good results were obtained without coated lenses.

Figures 1 and 2 represent a typical microscopical field of oolitic Clinton iron ore as photographed by conventional methods. Figure 1, taken with crossed nicols, shows a somewhat rounded crustacean fragment in the center of a field which is otherwise opaque except for a few quartz fragments and irregular carbonate areas. Figure 2, taken by reflected light, brings out the oolitic structure of the ore with the transparent minerals appearing opaque.

The same field is shown in Figure 3, illuminated by a combination of transmitted polarized light of low intensity and a strongly collimated beam of reflected plain light. By this method it is possible to recognize the crustacean fragment as forming an oolite nucleus. Other smaller oolites are noted attached to this larger structure. Small quartz grains, suggestive of oolite nuclei in Figure 1, are found to be non-oolitic and to occupy positions within bryozoan cells. The larger quartz fragment is also shown to be non-oolitic.

[1] Published by permission of the Director, Bureau of Mines, U. S. Department of the Interior.

[2] Associate mineralogist, Southern Experiment Station, Bureau of Mines, Tuscaloosa, Ala.

[3] Turner, A. F.: Coating lenses. Photo technique, October 1940, pp. 48–53; Blodgett, K. B.: Use of interference to extinguish reflection of light from glass. Physical Rev. 55: 391–404, 1939.

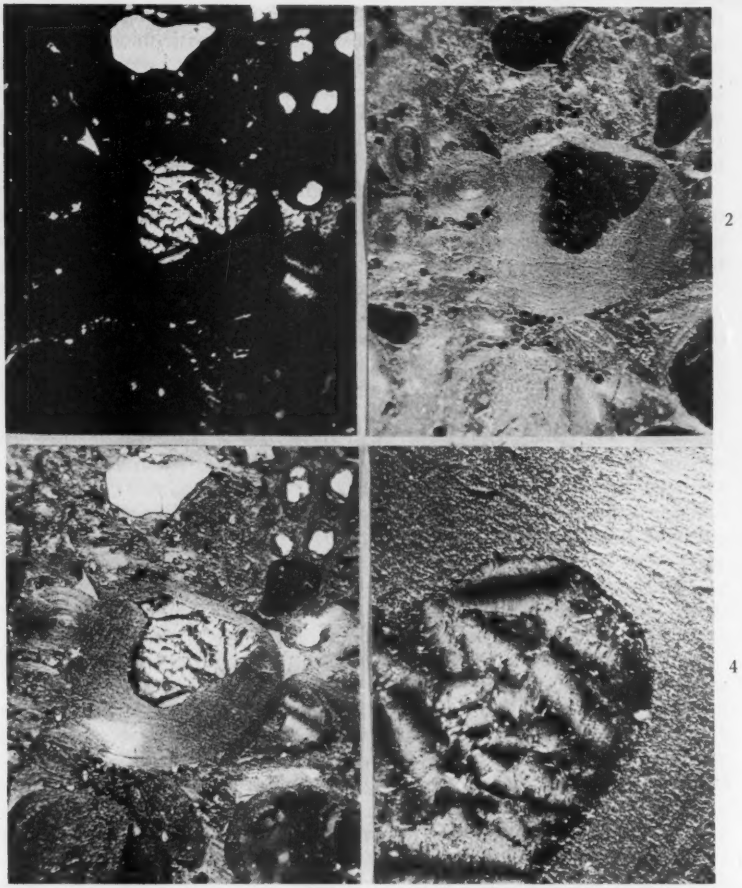

FIG. 1 (Upper Left). Iron ore, Wenona mine, Birmingham district, Alabama. Crossed nicols × 18. (Original magnification × 27.)

FIG. 2 (Upper Right). Same as Fig. 1, by reflected light.

FIG. 3 (Lower Left). Same as Fig. 1, by combined illumination.

FIG. 4 (Lower Right). Same as Fig. 3 with magnification × 60. (Original × 90.)

Figure 4 was prepared with the combined illumination under a higher magnification to bring out the concentric banded oolitic structure in greater detail. The bands are found to be made up of alternating hematite-clay layers. A chloritic mineral, or more likely a leptochloritic mineral—one of a chlorite-like group of definitely different composition—is rarely found in the banding and in the nucleus. Dark, brushlike structures within the oolite nucleus form the isogyres of interference figures. Fossil fragments of this type commonly show such figures without a conoscopic arrangement of the microscope.

Combined transmitted and reflected lighting in the study of oolitic iron ores has revealed unsuspected relationships. Its use can be recommended not only for this type of ore but for the detailed study of any ore containing both opaque and nonopaque minerals.

The work described above was performed at the Southern Experiment Station, Tuscaloosa, Alabama, W. H. Coghill, supervising engineer, in cooperation with the University of Alabama.

TUSCALOOSA, ALABAMA,
June 8, 1944.

OIL FOR THE FUTURE.*

WILLIAM B. HEROY.

FROM 1859 to the present moment the United States has occupied a peerless position as the world's chief source of petroleum. During 85 years of oil history this country has supplied about two-thirds of all the oil produced and in only half a dozen years has its contribution been less than half of the world's total supply. In the face of unprecedented demands for petroleum products to defend this country from its enemies, our production of oil has now reached new heights. Last year it just passed a billion and a half barrels, an amount which, even in these days of immense figures, is difficult to visualize. Perhaps it would help in completing the picture to say that this volume of oil would cover Manhattan Island to a depth of 12 feet.

The unprecedented demands for petroleum products to meet the requirements of the war program are testing the productive capacity of our wells and fields as never before. There are various indications that this production is not far from maximum—in fact it is evident that in many areas oil resources are being depleted far more rapidly than would be considered sound practice under normal conditions. This would be a cause for concern in itself but the gravity of the situation is increased by the recent decline in the rate of the discovery of new underground supplies to take the place of those that are being so rapidly depleted. This is a circumstance which, in my opinion, is of great significance in our national oil economy and I shall take a few moments to outline what has occurred.

For a period of two or three years after the discovery of the East Texas field in 1930 the immense flood of oil that resulted from its uncontrolled development dominated the market and there was little incentive to search for more oil. Commencing in 1934 and continuing through 1938, however, there ensued a period during which reserves were steadily increased as a result of new discoveries, approximately twice as much oil being found as was produced. Since 1938, however, that beneficial trend has not continued. In each of the five succeeding years discoveries of new reserves have failed to equal production. While inventories of proved reserves at the end of each of these years have shown increases, the annual increments have been progressively smaller. During 1943 the total increase in reserves barely balanced production.

This falling off in new discoveries would give less cause for concern if it had been paralleled by a decline in exploratory activity. Such, however, is not the explanation. Over 15,000 wildcat wells were drilled during this

* Presidential address delivered before the Society of Economic Geologists and American Institute of Mining and Metallurgical Engineers at the Annual Dinner of the Society, New York City, February 22, 1944.

period (1938–1943), probably a larger number than were drilled in any previous five years. In compliance with the desires of the Government, wildcat drilling has been intensified during the last two years. Activity in geophysical exploration has resulted in an all-time high. All this prospecting effort, furthermore, has resulted in the discovery of a record number of new fields and of new producing horizons in old fields. But the importance of these discoveries, measured in terms of volume of oil found, has gradually diminished. The size of the new-found fields has been most disappointing. Scarcely a field of major proportions has been found in the last two years.

It should, of course, be pointed out that there is an important element of chance in oil discovery and that the history of the industry records other periods when discoveries have been below normal. Perhaps, then, the recent dearth of discovery may be explained as due to our having passed through such a period, one when fortune was unfavorable, and, as a result of the operation of the law of equal expectations, we may rely upon the return of fat years following the lean.

Is there, then, any just cause for concern as to the future of our indigenous supply of petroleum? Can we expect that new discoveries will again replenish our underground inventories? Does the law of equal expectations or that of diminishing returns control the finding of oil deposits? These are questions to which no indisputable answers can be given. It is my hope, however, that I may interest you for a while in a discussion of some factors which, I believe, are significant in this connection.

Like most minerals, oil must be sought in the depths of the earth. Many deposits of minerals give the prospector definite surface clues of their presence and in some areas oil seepages have pointed to the existence of oil fields beneath. But, for the most part, oil is a highly elusive mineral and direct surface evidence of its presence is generally lacking. The search for oil fields, in the early years of the industry, was centered in areas where seepages were known and then, with the exhaustion of such indications, was carried on by drilling at random. In the first 40 years the industry as a whole knew of no other means of discovering oil and it became a proverb that "oil is where you find it."

It was only after the turn of the century that science began to be applied to the problem of finding oil. At first timidly, and then with greater assurance as he learned through trial and error, the petroleum geologist was able, through the mapping of the geology exhibited in the rocks exposed at the surface, to point out areas where wells would have a substantially better chance of being successful than if they were drilled at random. It was some time, however, before the industry became convinced that the geologist could "see farther" into the earth than anyone else. But the concept that oil occurred in "structures" gradually made its way and structure hunting had, by 1920, become the recognized guide to wildcatting.

In his search for suitable structures the petroleum geologist came to realize his need for more satisfactory working tools, techniques that could find structures not appearing on the surface and that would solve structural problems where surface evidence was incomplete. Applied geophysics was

born in the early twenties and the various types of investigation of the earth's subsurface which have subsequently been devised and developed together constitute a method with very marvelous resolving power for determining the position and attitude of the rocks beneath the surface. Thus applied science has gradually displaced random drilling as the predominant method of oil finding and today most exploratory wells are drilled on locations determined by geological evidence.

In its most recent manifestations the search for oil is carried on with the assistance of precision instruments that are capable, under satisfactory conditions, of structural determinations of a high order of accuracy. Small areas of closed structure a few hundred acres in extent can be accurately defined in many districts even where the key horizon is at a depth of five to ten thousand feet. Detailed work in such areas can scarcely be expected to leave any favorable structural features of economic importance undetected. In other areas, because of the weathering of surface rocks, or of irregularities in the underlying rocks, less precise results are attained but, even under such conditions, structural closures of a thousand acres or more should not escape detection. In some areas the difficulties encountered by seismograph operations are formidable and the results are still unreliable but these areas are diminishing and may in time be expected to yield results as techniques are further improved.

There are, of course, certain types of oil accumulations which are not due to structural causes. Many oil fields have accumulated in traps created by changes in porosity, the presence of unconformities, and the wedging out of reservoir beds. Such traps are generally difficult to detect by geophysical methods and are revealed only by extensive stratigraphic studies, by controlled exploratory drilling in prospective areas, or by wildcatting.

By the application of all these methods, about 50 billion barrels of oil have been found in the United States, of which about 28 billion barrels have already been produced, while about 20 billion barrels still remain in the ground as proved reserves. Less than a tenth of this total was found in the first forty years of the industry, up to 1900. During the following twenty years around 10 billion barrels, in the next decade about 18 billion barrels, and in the 13 years since 1930 another 16 billion barrels of oil have been discovered. By far the greater part of this immense volume of oil has been found since the introduction of geology and geophysics as methods of prospecting, and, although no complete survey has been made of the methods by which all of our more than 3000 oil fields have been discovered, it appears from the studies that have been made that the major part of these reserves has been discovered by the use of such technical methods.

In order to arrive at more definite conclusions as to how our oil has been discovered and our present reserves found, I have selected for study the 100 largest oil fields in the United States. By this I mean not the 100 fields that have produced the most oil but those which had the largest original oil content. Some of these fields are, of course, now far along to exhaustion, while some of them, those more recently discovered, still contain most of their original reserves. Practically all of these fields will have an ultimate re-

covery of over one hundred million barrels of oil and are, thus, major oil fields. These 100 fields had initial reserves, recoverable by current producing practices, totaling more than 30 billion barrels and thus originally contained about 65 per cent of all the petroleum that has been found in this country since the beginning of the industry. Of the fields studied, 39 are in Texas, 28 in California, and 13 in Oklahoma.

My inquiry has been directed to the determination of the susceptibility of these fields to discovery by structure-hunting methods. I have, accordingly, separated them into two groups,—first, those fields that have accumulated in traps of the structural type, such as anticlines, domes, and salt domes, which could be found by the application of structural mapping, either geological or geophysical; and, second, those fields that have accumulated in traps which are not readily found by the application of such methods, including those which are caused by slight unconformities and changes in facies.

Most fields of the non-structural type have probably been found by wildcat drilling. The East Texas field stands as the greatest monument to the wildcat driller. Others, like McKittrick, Midway, and Kern River, were drilled on seepages. Still others, such as Coalinga Nose and Santa Maria, have been found by careful stratigraphic studies.

Not less than 82 of these 100 major fields occur in structural traps while 18 fields are of types such that they would be difficult to find by the application of structure-hunting methods. About 21 billion barrels of the total of 30 billion barrels of initial reserves attributed to those 100 fields are found in the structural traps. By far the largest find in the non-structural group is, of course, East Texas. Aside from this field only about 4 billion barrels of initial reserves were contained in the major fields of stratigraphic types. Altogether, then, about 70 per cent of the oil of these 100 major fields was found in those of structural type.

Does the same proportion of oil occurring in structural traps, which is indicated by this study of major fields, apply to the 3,000 smaller fields? I have not attempted a complete analysis of this problem, a task of no small proportions. But review of lists of oil fields, such as those published annually by the American Institute of Mining and Metallurgical Engineers, indicates that the structural type of field is predominant and I can only express the personal conclusion that more than 75 per cent of our proved reserves occur in fields that have been or could reasonably be expected to be found by structure-hunting methods.

Studies of particular districts would also seem to confirm this conclusion. The Los Angeles Basin is one of our most prolific areas; it has produced nearly 3 billion barrels and has remaining proved reserves of another billion barrels in 34 fields, ten of which are in the major group. It has been intensively studied and no large area in the United States has been more thoroughly tested by exploratory drilling. From the standpoint of the character of the trap in which the oil has accumulated, 31 fields were found on anticlines and fault blocks, two are accumulations due to unconformities and one is a faulted monocline. The non-structural fields are all small and all of the great oil fields of the basin are of the structural type. Practically all

of the remaining reserves are found in structural traps. If important non-structural fields are actually present it seems reasonable to expect that they would have been found as the result of the large number of exploratory wells that have been drilled in the Basin.

Another area with great oil resources is the Gulf Coast district of Texas. It has produced over 1.7 billion barrels and has remaining proved reserves of over 3 billion barrels. It has more than 250 oil fields, 12 of which are of major size. All of the major fields and over 80 per cent of the smaller fields are of the structural type. This area also has been intensively tested by exploratory drilling.

The East Texas District has produced over two billion barrels and has a remaining proved reserve of several billion barrels. Five of its 60 fields are of major size, including the East Texas field, the outstanding American example of accumulation against an unconformable overlap. Extensive exploration in this district has found no other major fields of stratigraphic type. Fifty other fields in the district are of structural types.

The Illinois Basin has been thoroughly tested, commencing with the discovery of the Louden field in 1937. The unconformable overlap of the Pennsylvanian series on the older rocks effectively concealed the deeper structure and the area presented an excellent opportunity for the application of geophysical methods of structure finding. The initial successes achieved in the finding of two major fields have been followed by the discovery of many others of importance. Some 140 fields have been found in the last 6 years. The discovery of about half of these fields is attributed to seismic exploration; about 30 were discovered by random drilling; and nearly all the rest resulted from subsurface studies. In practically every case the oil has accumulated on a structural high. The sands of the upper part of the Mississippian series are lenticular and vary greatly in porosity, but the productive pools have, with rare exceptions, accumulated on structural uplifts. The underlying limestones similarly show great variations in porosity but they are oil-bearing on structural highs and not in off-structure areas. The billion and a half barrels of original reserves found in the Illinois Basin occur almost entirely in fields that have been or could have been found by structure-finding methods.

Other oil-bearing areas of the United States would, if examined in detail, doubtless show similar results. It must be concluded, I believe, from all the evidence, that by far the greater part of our known oil supplies have accumulated in traps which are detectable by geological and geophysical surveys.

While it is true that structural traps have been more easily detected by the techniques heretofore available, it does not follow that, if we could develop equally effective techniques for finding traps of the stratigraphic type, we would readily find a host of such new fields with total oil reserves comparable to those already discovered in fields of structural type. If traps of the stratigraphic type were inherently as numerous as those of the structural type, then the many thousands of wildcat wells which have been drilled in this country should have found, by the application of the law of averages, many more such fields than in the past.

But there is a still more convincing reason why more fields of the stratigraphic type have not been found, a reason which is fundamental to petroleum accumulation. Oil fields are generally found in sedimentary basins which lie between major uplifts. Some of these have just been used as illustrations. Many others, such as the San Joaquin Valley, the Bighorn Basin, the Delaware Basin, and the Appalachian Geosyncline, are household names to the American petroleum geologist. The many thousands of feet of sediments that are usually present in the deeper portions of such basins usually tend to thin out toward the margins of the basins against the surrounding uplifts. Such geological features as the wedging out of porous formations along ancient shorelines and the truncation of such formations under unconformable overlaps normally occur near the margins of these basins, for the interior areas have generally been more stable geologically. The margins of the basins have been the locus of more numerous facies changes, have experienced more minor uplifts and depressions, and have been more exposed to deformation caused by pressure from adjoining positive areas. These marginal areas are, therefore, the principal habitat of traps of stratigraphic type.

In contrast, the structural type of trap may occur not only along or near the margin of the basin but may be distributed quite generally throughout its entire area, depending upon the nature of the stresses to which the basin may have been subjected. In typical basins more geological features favorable to oil accumulation are situated in central positions as compared with the number in marginal positions. To revert to the Los Angeles Basin, for purposes of illustration, only three fields lie along the rim of the basin while the remaining 31 are generally distributed through its interior.

Wedge belts, shorelines, and truncations are essentially linear features. Even though porous beds suitable for reservoirs may continue throughout the entire extent of such features it does not follow that all portions of such beds are equally favorable for oil accumulation. The principle of buoyancy is the controlling one, and oil will tend to accumulate along the relatively high portions of the porous wedge, leaving the lower portions to be filled with water. Structural noses and folds crossing the porous wedge will be the normal points of oil accumulation while the intervening saddles will be barren. As an example, the Coalinga Nose field in the San Joaquin Valley results from a combination of up-dip change from sandstone to shale with the presence of a large structural nose. Careful work along the entire west side of the San Joaquin Valley, along the probable southward extension of this sandstone, has failed to reveal the presence of another of such nose which might be the locus of similar field. The opportunities for such combinations are not too numerous and it will be only at widely-spaced intervals along wedge belts of porosity that we may, in consequence, expect to find conditions favorable to oil accumulation.

If these two conclusions are sound,—

First, that our methods of finding structures have been, on the whole, highly effective and we are now reduced to seeking the less conspicuous structural features, and

Second, that the amount of oil to be found in stratigraphic traps is

materially less than that inherently occurring in structural traps,—what shall we conclude as to our future oil prospects?

Surely it would be wishful thinking confidently to expect to continue indefinitely to discover new fields adequate to supply the heavy demands of our motorized civilization. Oil is not being created at any perceptible rate and each new field found and developed is to be subtracted from the undiscovered but finite remaining reserve. We cannot escape the operation in oil finding of the law of diminishing returns and we should not lightly disregard those signs which point to the effectiveness of its operation.

I can discover no sound reason for believing that the pattern of oil distribution, as regards type of accumulation, is likely to change in the future in any fundamental respect. More refined techniques and more intensive surveys will continue to furnish structural information of greater reliability; more precise studies of sedimentation and more accurate correlations will reveal many additional areas favorable to non-structural accumulation. These further applications of science, in combination with deeper drilling, will make possible the more complete testing of the deeper portions of our great sedimentary basins, sometimes below several unconformities, where most of our undiscovered reserves will be found. But by far the larger part of the newly discovered oil will continue, as in the past, to occur in traps than can be detected by structural methods of prospecting.

MEMORIAL TO PROFESSOR HENRY LLOYD SMYTH.

PROFESSOR SMYTH was born at St. Mary's, Ontario, Canada, January 11th, 1862, to Thomas H. Smyth, Episcopal clergyman, and Charlotte E. (nee) Hughes, his wife. He died April 1st, 1944, at his home, Plainfield, New Hampshire. He was educated at Harvard University, A.B. (magna cum laude) 1883; C.E. 1885. On November 8th, 1894 in Brighton, England, he married Margarita Pumpelly, daughter of the great geologist and explorer, Raphael Pumpelly. The two had four children: Charlotte Smyth Russell (Deceased), Pauline Smyth Otis, Henry Lloyd Smyth, Jr. (Deceased), and Barbara Smyth Boeckler. Professor Smyth always expressed especial gratitude for the influence of Dr. Pumpelly, and of Professor Shaler, Dean Eustis, and James Mills Pierce, the mathematician, all of Harvard.

His early professional work was with the United States Geological Survey, and resulted in publications on the geology of the Marquette and Menominee Ranges in the monographs of that Survey, which are still authoritative.

His publications, on the Michigan copper deposits, on magnetic surveying, on the Vermillion Range, on mining practice, on Vermont copper deposits, and other subjects, are notable, extensive, and of basic value. His work on the structural geology of Steep Rock Lake, Ontario, published in 1891, is fully borne out by current developments at the great iron deposits there.

He was Chief Geologist of Cleveland Cliffs Iron Company, from 1899 to 1927, during which period he vastly increased the ore reserves and the resulting importance of this great Lake Superior mining company. The Cliffs Shaft Mine had 60,000 tons of ore available in 1898. As a result of Smyth's detailed and scientific solution of its complex geology, it has since produced upward of 15 million tons, largely premium grade hard ore, and is still one of the great iron mines. He discovered the Swanzy district mines, including the Austin, Gwinn, Mackinaw-Gardner, and Princeton mines. The Athens, Barnes-Hecker, Lloyd and Morris mines were discovered by him, and the North Lake, Maas, Negaunee and Salisbury mines were largely extended by his work. His accomplishment is thus permanently knit into the steel framework of the nation, and aids today in defeating the forces of evil.

His technical ability was quite equalled by his business acumen. Certain exchanges of mineral land promoted by him between the Cleveland Cliffs and Oliver Companies resulted in great gain to *both* companies. He was Chairman of the Keweenaw Land Association and President of Newport Land Company, two great Michigan iron ore, timber and land concerns, from 1922 to 1943.

He taught geology and mining at Harvard from 1893 to 1924, and was chairman of the Department (later Division) of Mining and Metallurgy from 1904 on. In his students and their work he lives on, respected, emulated, and loved.

As a humanitarian, he did much to increase the safety and welfare of the industry. He was essentially the founder of the Safety and Welfare work of Cleveland Cliffs, a pioneer in this line, and his studies of mine accidents were at the source of much of the work which has changed iron mining from a most hazardous, to one of the safest, of industries.

His ore discoveries have provided the livelihood and happiness of thousands of families; and his humanitarianism has saved the lives and limbs and health of countless bread winners, who do not even know the name of this loyal, scientific, intellectual gentleman and scholar. "Inasmuch as ye have done it unto one of the least of these, my brethren, ye have done it unto me."

STEPHEN ROYCE.

DISCUSSION AND COMMUNICATIONS

VIOLARITE AND BRAVOITE.

Sir: The paper by C. E. Michener and A. B. Yates on Oxidation of Primary Nickel Sulphides (ECON. GEOL. No. 1944, pp. 506–514) presents a description and interpretation of some phenomena which make very satisfactory reading because substantiated by such unequivocal good evidence. I have read with deep interest the papers dealing with secondary nickel-bearing sulphide minerals ever since I allocated a few hours to myself in 1924 to determine a secondary nickel mineral from the deposits of Yakobi Island, Alaska, and ended up after 6 weeks of study by calling it "nickel mineral X" (ECON. GEOL. 1924, pp. 521–541). Despite all the work that has been done since that time, I think that the nature of certain supergene nickel-bearing sulphides is still in a most unsatisfactory state.

Many papers have shown that there is a secondary nickel mineral of supergene origin which has similar properties to those of the Sudbury violarite for which a chemical analysis is available. I should like to point out, however, that the original Sudbury violarite has not been demonstrated to be of supergene origin and has a somewhat different mode of occurrence and relationships as compared to the mineral of proven supergene origin. The same situation applies to the analyzed secondary nickel mineral from Julian, Calif. Short and Shannon interpreted the violarite at both these localities as hypogene. Nobody, to my knowledge, has yet provided a chemical analysis of a sample of the mineral, called by many violarite, which by common acknowledgment is considered supergene. This is necessary to really complete the proof of its identity with the Sudbury violarite. May we hope that somebody, somewhere, sometime, will find this supergene mineral in such quantity and occurrence that it can and will be isolated and chemically analyzed.

Another nickel mineral which is found as a supergene replacement is bravoite. Rasor (ECON. GEOL. 1943, pp. 399–407) writes of bravoite described by him from Missouri as being the first occurrence of this mineral to be found in North America. I have published a chemical analysis (ECON. GEOL. 1924, p. 525) by A. H. Phillips of a mineral from Canyon Creek, Copper River, Alaska, which I interpreted to conform to the formula for bravoite. One is left to wonder whether this reference was overlooked or whether it is thought by Rasor that the Alaska mineral is not bravoite. The paper of Michener and Yates describes the occurrence of nickeliferous pyrite in as-

sociation with marcasite as replacements of pyrrhotite in many gossan outcrops. The supposed bravoite of the Alaska occurrence also is associated with marcasite in outcrops. Short and Shannon state that they are inclined to question the purity and therefore the chemical analysis of the mineral originally described as bravoite from Minasragra, Peru. They note that the properties of the mineral originally described as bravoite and the Sudbury violarite are similar, which raises the possibility of their identity. Obviously then there is also a problem to be solved here.

A. F. BUDDINGTON.

REVIEWS *

BOOKS RECEIVED.

RALPH E. DIGMAN.

U. S. Geological Survey. Washington, 1944.

Bull. 933-C. **Relations of Structure To Mineral Deposition At the Independence Mine, Alaska.** WALTER STOLL. Pp. 16; Figs. 4; Pls. 5. Price, 15 cents.

Bull. 935-D. **Tungsten Deposits Isla De Pinos, Cuba.** L. R. PAGE AND J. F. MCALLISTER. Pp. 69; Pls. 12. Price, $1.25.

Bull. 935-E. **Nickel-Silicate and Associate Nickel-Cobalt-Manganese-Oxide Deposits Near Sal Jose Do Tocantins, Goiaz, Brazil.** W. T. PECORA. Pp. 58; Figs. 3; Pls. 7. Price, $1.00.

Bull. 935-F. **Manganese Deposits in Part of the Sierra Maestra, Cuba.** C. F. PARK, JR. AND M. W. COX. Pp. 48; Figs. 4; Pls. 17. Price, 75 cents.

Bull. 935-H. **Manganese Deposits in Costa Rica.** RALPH ROBERTS. Pp. 27; Figs. 10; Pls. 3. Price, 15 cents.

Bull. 936-R. **Manganese Deposits in the Artillery Mountains Region Mohave County, Arizona.** S. G. LASKY AND B. N. WEBBER. Pp. 31; Figs. 2; Pls. 8. Price, $1.25.

Bull. 937. **Bibliography of North American Geology. 1929–1939.** EMMA THOM. Pp. 1065. Price, $2.50.

Bull. 940-G. **Manganese Deposits of the Sweet Springs District, West Virginia and Virginia.** HARRY S. LADD. Pp. 18; Figs. 2; Pls. 2. Price, 35 cents.

Bull. 940-I. **Tungsten Deposits in the Boriana District and the Aquarius Range Mohave County, Arizona.** S. W. HOBBS. Pp. 17; Figs. 2; Pls. 6. Price, 40 cents.

Bull. 942. **Geological and Geophysical Survey of Fluorspar Areas in Hardin County, Illinois.** L. W. CURRIER AND M. K. HUBBERT. Pp. 149, Figs. 31, Pls. 24. Price, $1.25.

Bull. 943-A. **Mineral Industry of Alaska in 1941 and 1942.** PHILIP SMITH. Pp. 23. Price, 10 cents.

Prof. Pap. 142-G. **The Molluscan Fauna of the Alum Bluff Group of Florida.** JULIA GARDNER. Pp. 54; Pls. 3. Price, 25 cents.

Prof. Pap. 204. **Geology of the Hanover-York District, Pennsylvania.** A. J. STOSE AND G. W. STOSE. Pp. 83; Figs. 29; Pls. 18. Price, $1.75.

Wat. Supply Pap. 889-C. **Ground-Water Resources of the Houston District, Texas.** W. N. WHITE AND OTHERS. Pp. 49; Figs. 6; Pls. 4. Price, 35 cents.

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

Wat. Supply Pap. 889–D. **Exploratory Water-Well Drilling in the Houston District.** N. A. ROSE AND OTHERS. Pp. 24; Figs. 5; Pls. 5. Price, 15 cents.

Wat. Supply Pap. 889–E. **Chemical Character of Surface Waters of Georgia.** WILLIAM LAMAR. Pp. 63; Figs. 11. Price, 15 cents.

Wat. Supply Pap. 914. **Texas Floods of 1938 and 1939.** S. D. BREEDING AND T. DALRYMPLE. Pp. 116; Figs. 21; Pls. 8. Price, 25 cents.

Wat. Supply Pap. 945. **Water Levels and Artesian Pressure in Observation Wells in the U. S. in 1942. Part 2. Southeastern State.** O. E. MEINZER AND OTHERS. Pp. 162; Figs. 14. Price, 25 cents.

Wat. Supply Pap. 946. **Water Levels and Artesian Pressure, etc. Part 3. North-Central States.** O. E. MEINZER AND OTHERS. Pp. 278; Figs. 11.

Wat. Supply Pap. 951. **Surface Water Supply of the United States, 1942. Part 1. North Atlantic Slope Basins.** G. L. PARKER AND OTHERS. Pp. 609; Pl. 1.

Wat. Supply Pap. 952. **Surface Water Supply of the U. S. Part 2. South Atlantic Slope and Eastern Gulf of Mexico Basins.** G. L. PARKER AND OTHERS. Pp. 477; Pl. 1. Price, 60 cents.

Wat. Supply Pap. 962. **Surface Water Supply of the U. S. Part 12. Pacific Slope Basins in Washington and Upper Columbia River Basin.** G. L. PARKER AND OTHERS. Pp. 231; Pls. 2. Price, 30 cents.

Wat. Supply Pap. 963. **Surface Water Supply of the U. S. Part 13. Snake River Basin.** G. L. PARKER AND OTHERS. Pp. 232; Pl. 1. Price, 30 cents.

U. S. Bureau of Mines. Washington, 1944.

Bull. 458. **Quarry Accidents in the United States (1942).** W. W. ADAMS AND V. E. WRENN. Pp. 89; Figs. 3. Price, 15 cents.

Tech. Pap. 652. **Analyses of Kentucky Coals.** Pp. 307; Figs. 13. Price, 40 cents.

Tech. Pap. 659. **Analyses of Pennsylvania Anthracitic Coals.** Pp. 259, Figs. 10.

Tech. Pap. 663. **The Flow of Coal-Ash Slag on Furnace Walls.** P. COHEN AND W. T. REID. Pp. 22; Figs. 7. Price, 10 cents.

Tech. Pap. 665. **Production of Industrial Explosives in the United States (1943).** W. W. ADAMS AND V. E. WRENN. Pp. 26; Figs. 2. Price, 10 cents.

Tech. Pap. 666. **Bureau of Mines Research on the Hydrogenation and Liquefaction of Coal and Lignite.** A. C. FIELDNER AND OTHERS. Pp. 69; Figs. 30.

Tech. Pap. 667. **Carbonizing Properties of Western Region Interior Province Coals and Certain Blends of These Coals.** J. D. DAVIS AND OTHERS. Pp. 138; Figs. 91. Price, 20 cents.

Tech. Pp. 670. **Carbonizing Properties of Pocahontas No. 3-Bed Coal from Kimball, McDowell County, W. Va., and the Effect of Blending this Coal with Pittsburgh-Bed Coal.** J. D. DAVIS AND OTHERS. Pp. 35; Figs. 22. Price, 10 cents.

Miners' Circular 45. **Explanation and Justification of Tentative Inspection Standards for Bituminous-Coal Mines and Lignite Mines.** Pp. 134.

Bed-Load Transportation in Mountain Creek. H. A. EINSTEIN. Pp. 54; Figs. 32. U. S. Dept. of Agriculture, Washington, 1944.

Arizona Nonmetallics. E. D. WILSON. Pp. 58. Bull. 152, Arizona Bureau of Mines. Tucson, 1944. Price, 30 cents.

Artesian Water in Southeastern Georgia. M. A. WARREN. Pp. 140; Figs. 34. Bull. 49, Georgia Geological Survey. Atlanta, 1944.

Tabular Description of Outcropping Rocks in Kansas. R. C. MOORE AND OTHERS. Pp. 75; Figs. 9. Bull. 52, Part 4, Kansas Geol. Survey. Lawrence, 1944.

Mined Areas of the Weir-Pittsburgh Coal Bed. G. E. ABERNATHY. Pp. 15; Fig. 1; Pl. 1. Bull. 52, Part 5, Kansas Geol. Survey. Lawrence, 1944.

Geology and Ground Water Resources of Finney and Gray Counties, Kansas. BRUCE LATTA. Pp. 268; Figs. 21; Pls. 12. Bull. 55, Kansas Geol. Survey. Lawrence, 1944.

Geology and Underground Waters of Southern Minnesota. GEORGE THIEL. Pp. 498; Figs. 91. Bull. 31, Minnesota Geol. Survey. Minneapolis, 1944.

Mississippi Minerals. WILLIAM MORSE. Pp. 13. Bull. 59, Mississippi Geol. Survey. University, 1944.

Aerogeology in Mineral Exploration. W. S. LEVINGS. Pp. 77; Figs. 12. Quarterly of the Colorado School of Mines. Golden, 1944. Price, $1.00. *An excellent number in which are discussed instruments and technique of photoflying, geological features observed on airplane photos, classification of aerial maps, applications in geological exploration, and new developments in air photography. Several fine halftones of air photos are inserted to illustrate the text.*

Petroleum, Past, Present and Future. PER FROLICH. Pp. 25; Figs. 13. Industrial and Engineering Chemistry.

Mining in the Netherlands East Indies. ALEX L. TER BRAAKE. Pp. 110; Pls. 10. Bull. 4 of the Netherlands and Netherlands Indies Council of the Institute of Pacific Relations. New York, 1944. Price, 50 cents.

Bureau of Mines Research on the Hydrogenation and Liquefaction of Coal and Lignite. A. C. FIELDNER AND OTHERS. Pp. 19, Figs. 7. Tech. Pub. No. 1750, American Institute of Mining and Metallurgical Engineers. 1944.

SOCIETY OF ECONOMIC GEOLOGISTS

The Annual Meeting of the Society, scheduled for February 20–22, 1945, in New York, has been cancelled. This is in accord with the well known request of the Honorable James F. Byrnes, Washington, D. C. The Council Meeting will be held February 20, and the Annual Business Meeting and address by President John M. Boutwell will take place at 7 P.M., February 20.

The nomination of Dr. Jorge A. Broggi was sponsored by Drs. L. C. Graton, D. H. McLaughlin, and A. M. Bateman and not, as originally announced in the printed form sent to members, Drs. F. W. DeWolf, Arthur Bevan, and H. S. McQueen.

SCIENTIFIC NOTES AND NEWS

This issue of this magazine goes to the printer nearly two months late owing to unavoidable delays.

W. L. WHITEHEAD, who has been in charge of geological exploration for aluminum ores in Haiti, Puerto Rico, the Dominican Republic, Cuba and Mexico for Reynolds Metals Company, has recently returned to the Massachusetts Institute of Technology. Discoveries of bauxite made in Haiti by the field parties, which included R. R. Shrock and Forbes Robertson, are being developed under the direction of Carl Schmedeman, chief geologist of Reynolds Mining Company.

DR. G. M. SCHWARTZ, Professor of Economic Geology at the University of Minnesota, has been on leave since June 15th, 1944, during which time he has been investigating various types of copper deposits for the United States Geological Survey. He has spent most of the time in Colorado and Arizona directing the exploratory work on porphyry ores. He will return to his duties at the University of Minnesota when class work begins in January.

The Mineralogical Society of America will hold a luncheon at the Pennsylvania Hotel in New York City on Tuesday, February 20, the occasion being the Award of The Roebling Medal to Professor Edward H. Kraus, Dean of the College of Literature, Science, and the Arts, University of Michigan. The luncheon will be held from 12:15 to 2:00 o'clock. Members and friends of the Society and friends of Dean Kraus are cordially invited. Detailed information may be obtained by communicating with C. S. Hurlbut, Jr., Department of Mineralogy, Harvard University, Cambridge, Mass.

The death is announced of Dr. Charles J. Muller, Assistant to the Vice-President in charge of Raw Materials, of the United States Steel Corporation of Delaware, on November 16, 1944. Dr. Muller was well known for his geological work on the Lake Superior ranges and from his examinations in foreign fields, having visited and investigated every important iron deposit in North and South America and most of the European deposits. His professional work included examinations of deposits of other minerals essential to the steel industry. Dr. Muller's passing is mourned by a host of friends.

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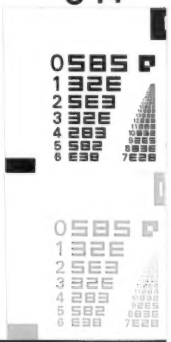
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